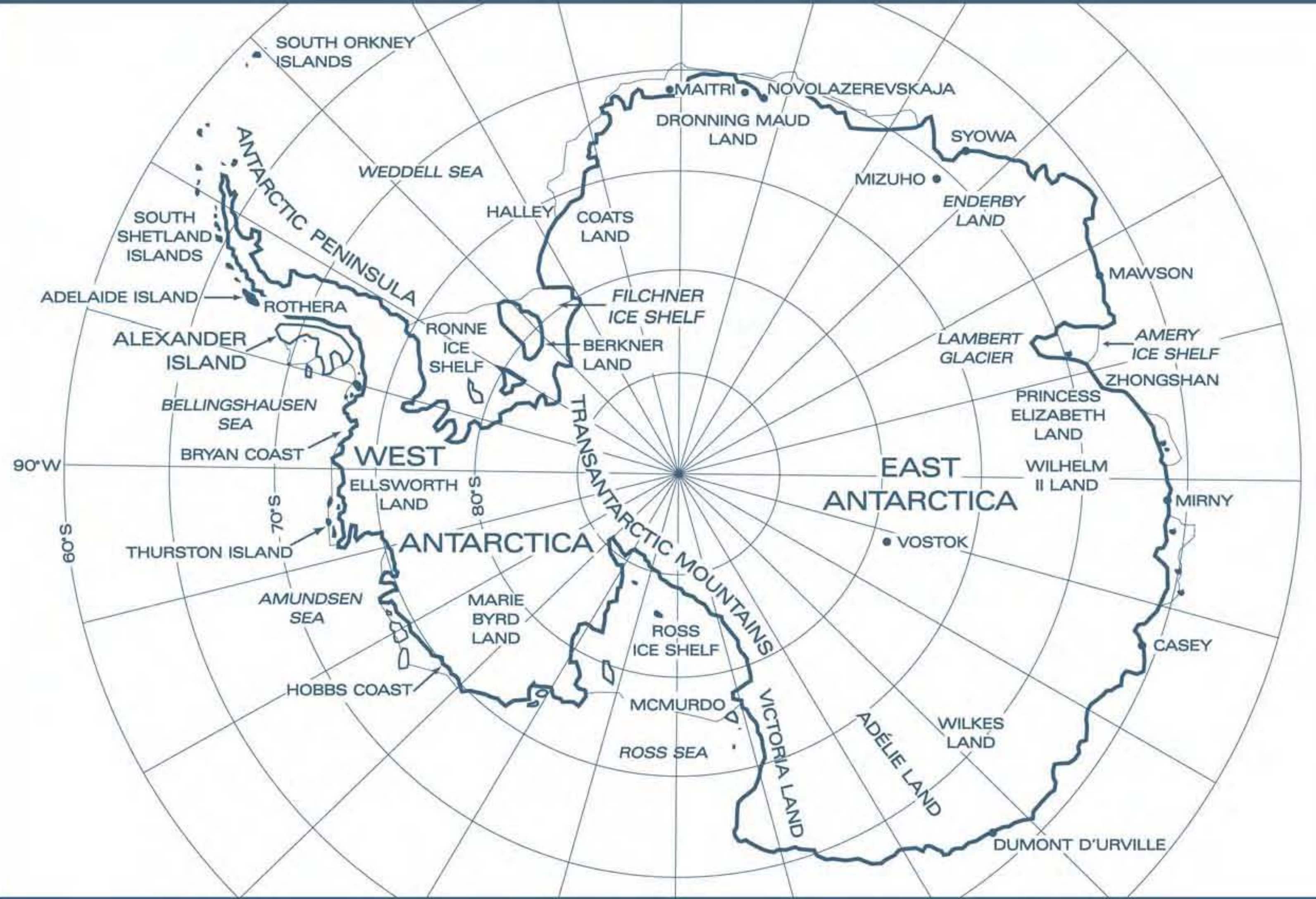
ENCYCLOPEDIA OF THE ANTARCTIC

VOLUME 1
A–K
INDEX



Beau Riffenburgh
EDITOR

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INTRODUCTION

The Antarctic is unique: geographically, politically, and scientifically. It is the most remote, hostile, and naturally dangerous continent, while at the same time it is the most pristine and least developed. Antarctica is the only major part of the Earth's landmass not directly governed by one nation; rather, it exists under the control of a carefully developed, although still evolving, treaty, which has a multitude of acceding nations. It is the only place in the world in which claims of ownership have been set aside. International agreements that ban nuclear testing contain damage to the environment under specific regulations and replace international competition with scientific investigations and organizations link nations in sustained, peaceful joint efforts.

Despite its isolation and harsh environment, the Antarctic is home to, or major feeding grounds for, large populations of wildlife. The largest living animals on the Earth, blue whales, can be found there, as can a wide variety of other whales, seals, and many more species of marine life. Some of the world's largest flying birds—wandering albatrosses with wing spans of 3 m and southern giant petrels—can be found in the region, as can a number of different species of penguins, including the emperor, which can weigh up to 35 kg. At the other end of the size spectrum, the terrestrial Antarctic hosts population densities of tardigrades between ten and one thousand times greater than those of temperate or tropical zones. There are also particularly abundant groups of microorganisms, many considered extremophilic, living under extreme conditions that they not only tolerate, but also need in order to exist.

Another Antarctic visitor, in relatively modern times, has been humans. In the nineteenth century, the Southern Ocean surrounding the Antarctic continent was prized as a source of wealth in the form of whale and seal oil and blubber. Around a century ago, the mainland itself became the focus of geographical exploration and the compilation of scientific data. In more recent decades, particularly since the International Geophysical Year of 1957–1958, the major human emphasis placed on the terrestrial, ice, marine, and atmospheric aspects of the southern polar region has been on scientific investigation and increasing our knowledge of the Earth and beyond. In this way, the Antarctic has been shown to be much closer to the rest of the planet than had earlier been thought, because it is a key component of many global systems, including climate, weather, oceanographic circulation patterns, complex interactions in ecosystems, and the influence of the stratosphere (including the ozone layer) in the reception of solar radiation planetwide.

Intriguingly, for an area of such importance, there is not a single, universally accepted definition for what the Antarctic is, because the region has variously defined boundaries for different purposes. Some consider it to be the continent itself, and there is debate as to whether the floating ice shelves that are seaward extensions of the continental ice sheet form an integral part of the "land" surface of the continent. There is also a question of whether this definition includes the islands immediately adjacent to the continent, many of which are attached to the continent by ice shelves. Along and above the Antarctic Peninsula, the off-lying islands are also sometimes regarded as part of the continent.

A purely geographical definition of Antarctica is the area south of the Antarctic Circle (at 66°33′39″ S), below the latitude at which the sun does not rise on Midwinter Day and does not set on Midsummer Day. A political boundary is the area south of 60° S latitude, the northern limit of jurisdiction for the Antarctic Treaty, which became effective in 1961 with twelve original signatories and now has been acceded to by forty-five countries.

Perhaps the consensus of Antarctic scholars is that the best boundary is the Polar Front (formerly known as the Antarctic Convergence), an irregular belt in the Southern Ocean some 20 miles wide occurring between 48° S and 61° S. This is where the cold, dense waters of the Southern Ocean sink beneath the warmer surface waters of the southern Atlantic, Pacific, and Indian oceans, marking a distinct change in the surface temperature and chemical composition, which in turn affects the creatures living on either side of it. This is both an ecosystem boundary for many marine species and an administrative boundary; it was chosen by the Convention for the Conservation of Antarctic Marine Living Resources for the extent of its jurisdiction. It is also the boundary adopted by the Scientific Committee on Antarctic Research because it is defined by natural features, including the northern limit of the Antarctic Circumpolar Current.

Many, but not all, of the sub-Antarctic islands and island groups are within the Polar Front. Those islands and island groups lying south of the Polar Front, but not forming part of the Antarctic continent, include Bouvetøya, Heard Island, the MacDonald Islands, the Balleny Islands, Scott Island, Peter I Øy, South Georgia, the South Orkney Islands, and the South Sandwich Islands.

All these definitions and aspects of the Antarctic are only small parts of the diverse, multifaceted, and hugely significant area of the world introduced, explained, and covered in detail in the *Encyclopedia of the Antarctic*. The two volumes of this work comprise overviews and in-depth discussions of people, historical events, places, wildlife, scientific research, our place in and use of the environment, technological developments, and geopolitics. They also explain the host of scientific studies for which the Antarctic has become an international center, including geophysics, glaciology, atmosphere and climate, solar-terrestrial physics, astronomy, human impacts, oceanography, terrestrial and marine biology, geology, botany, and sea ice. These volumes are the result of the combined efforts of more than three hundred international scholars and experts in many fields, most of whom have dedicated their lives to the study, understanding, and preservation of the Antarctic.

All of this makes the *Encyclopedia of the Antarctic* a unique resource and tool for a wide readership of students, researchers, scholars, and anyone with a general interest in the region of the Antarctic, sub-Antarctic, and Southern Ocean. It both examines the broad, complex theoretical context and fills in the specific details of the existing knowledge about the Antarctic—its history, life forms, and influence on the rest of the Earth, as well as its place in our scientific understanding of the world.

The goal of this project was to produce a comprehensive, multivolume work that would cover the entire scope of Antarctic knowledge. Of course, even in two volumes this is impossible, but the *Encyclopedia of the Antarctic* is larger, more thorough, and more inclusive than any previous work of its kind. The encyclopedia took shape through the contributions of many people, most importantly an advisory board consisting of internationally distinguished scholars who drew up lists of topics in their fields, determined suitable lengths for the entries, and suggested appropriate authors. This all reflected a degree of subjectivity, of course, which was tempered by the process of the advisors, each helping to refine the subsequent overall list of topics, and by the countless suggestions for improving the content that were received from scholars throughout the world. Several authors who were given assignments believed that other topics were of such importance that they voluntarily wrote and submitted extra entries, which were in turn assessed for their viability as part of the encyclopedia. Input from the advisors, authors, and other scholars around the world continued throughout the development and writing of the encyclopedia, and the list of entries was revised virtually until the volumes went to production, allowing it to provide a reliable, up-to-date view of the current state of scholarship about the Antarctic.

The *Encyclopedia of the Antarctic* comprises 495 free-standing, alphabetically ordered entries of 500 to 6000 words in length. These range from factual, data-driven entries, such as biographies, wildlife details, and statements about national Antarctic programmes, to longer overviews on major themes and analytical discussions of issues that are of significant interest to both scientific researchers and the general public, such as climate change, conservation, geopolitics, biogeography, and pollution.

How to Use This Book

Although each entry is self-contained, the links between the entries can be explored in a variety of ways. The **Thematic List of Entries** in the front matter of each volume groups the entries within broad categories and provides a useful summary. Cross-references **(See also)** given at the end of almost all entries refer the reader to other related topics within the encyclopedia. Each entry also contains a list of **References and Further Reading,** including sources used by the writer as well as additional items that may be of interest to and expand the knowledge of the reader. Seven **Appendices,** including the text of the Antarctic Treaty, and sixteen **Maps** further guide the reader in exploring the features of this vast region. A thorough, analytical **Index** provides a detailed listing of topics that help the reader navigate through the wealth of information provided within the entries.

Acknowledgments

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LIST OF ENTRIES A–Z

F

G

H

I

T

U

V

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THEMATIC LIST OF ENTRIES

Geography

Geology

Glaciology

History, Exploration, and History of Science

Marine Biology

Marine Mammals

Oceanography

Research Programs, International Organizations, Atlantic Treaty System

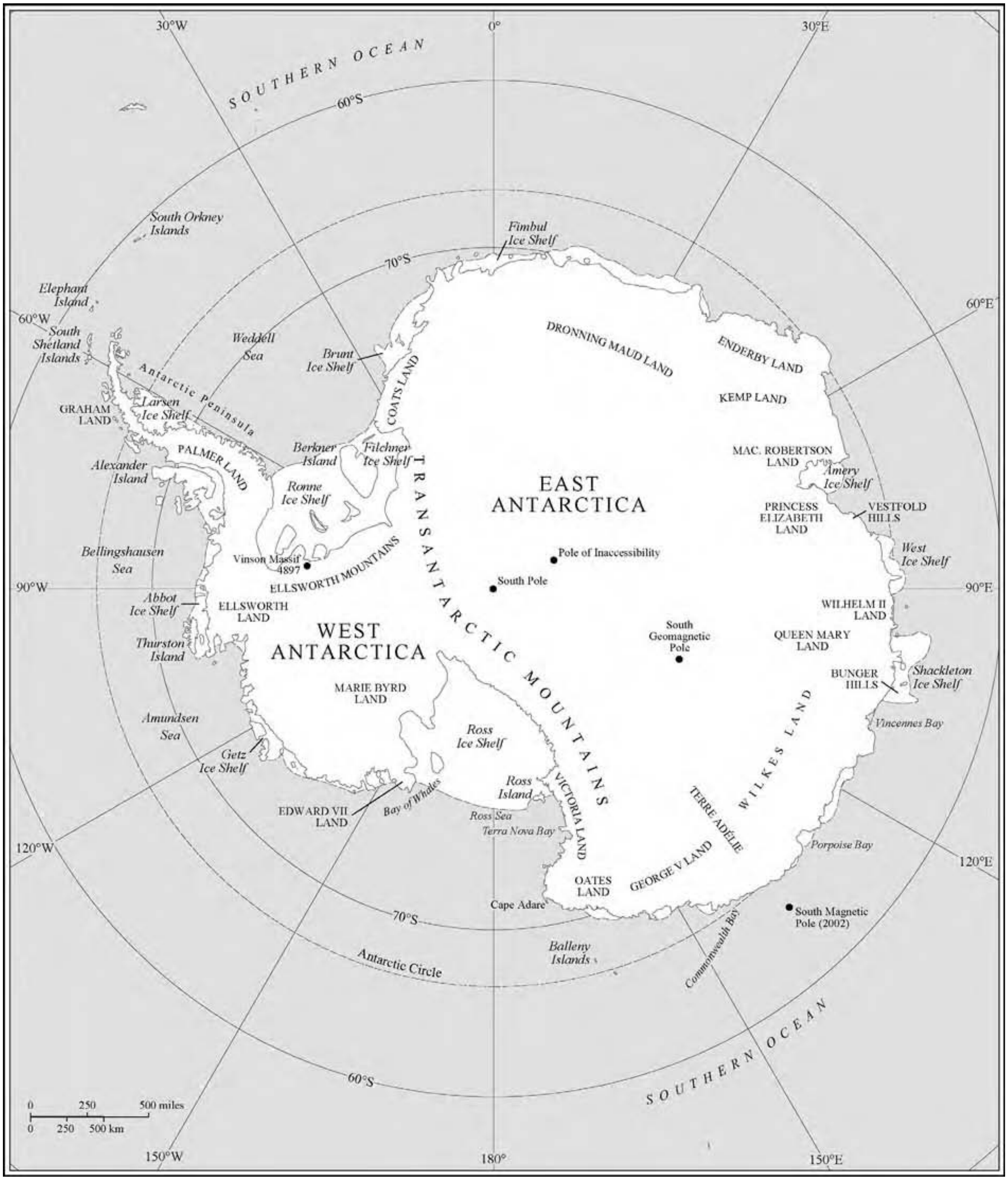
Sea Ice

Solar-Terrestrial Physics and Astronomy

Technology and Transport

Terrestrial Biology and Limnology

MAP OF ANTARCTICA



MAP OF THE ANTARCTIC PENINSULA

A

ADAPTATION AND EVOLUTION

The term *evolution* can be used with different interpretations, dependent on the context. Two broad generalisations are useful to recognise. First, in everyday use across many disciplines and subject areas within and outside science, "evolution" is often used simply to describe processes of change or development. Second, within evolutionary biology, its use is associated with very precise definitions. Here, it is used in the context of the fundamental processes by which biological change occurs, developing from concepts originally proposed in the nineteenth century and made famous by the mechanism of natural selection independently proposed by Charles Darwin and Alfred Russell Wallace. These recognise that the characteristics of living organisms are not simply determined by the environment around them, but also by features passed on or inherited from their parent(s). It is in the latter sense that the concept of evolution will be examined here in the context of Antarctic biology.

It was many years after the lives of Darwin and Wallace before the mechanism of inheritance was discovered, through Crick and Watson's pioneering work on the structure of the nucleic acid DNA (deoxyribonucleic acid). Nucleic acids such as DNA are very long polymer molecules, made up of chains of nucleotide subunits, and these chains provide the genetic code for all the proteins that, ultimately, contribute to all of an organism's activities, from intracellular biochemical processes to their morphology and behaviour, and the interactions that are seen. This code is carried in the form of *genes,* which are specific sequences of nucleotides coding for a particular protein. All living organisms contain their own unique genetic "blueprint," and it is this that is passed on to future generations in the various processes of reproduction that exist. During all forms of reproduction, these chains are copied to give rise to new individual organisms. However, the process is not perfect, and "copying errors" can occur, introducing variation. Furthermore, in sexual reproduction the DNA of the two parents is "mixed," giving rise to new combinations of genes. This results in offspring that differ in (often minute) detail from their parents, and thus have different abilities to function effectively in their environment. Therefore, some are inevitably more successful than others and, importantly, can then contribute relatively more offspring of their own into the next generation. These offspring, or at least some of them, will carry the successful characteristic in their own DNA, providing a new starting point from which the process of change can continue.

The process by which the influence of environmental characteristics on organisms leads to differential success is known as *natural* selection. Over time, the consequence that is seen (of gradual and, occasionally, rapid change) is described as *evolution by natural selection*. The related term *adaptation* is used to describe the features that have progressively developed in response to selection, and allowed some organisms greater success during the evolutionary process, while the term *fitness* is used to describe the relative success of an organism in passing on its genetic material to future generations. It is important to note that, in terms of strict definition, this terminology can be applied only in circumstances where the biological features of concern are controlled in some part through heritable variations in genetic material (*genotypic* variation), and do not apply in circumstances where there is no heritable component and all variation encountered is only in direct response to the environment (purely *phenotypic* variation).

Evolutionary processes ultimately underlie the patterns of diversity that are seen now (and also at any other time in the history of life), as progressive accretion of evolutionary changes may eventually lead to reproductive isolation and speciation. Here, the contrast between Antarctic terrestrial and marine environments provides a striking illustration. On land, diversity is low in all groups of biota, while on the marine continental shelf it is very high. Both these features are driven by the history of Antarctic glaciation over geological and evolutionary time. Even today, terrestrial habitats comprise a small proportion of continental surface area, and are generally individually of limited extent and often very isolated, while the marine continental shelf is extensive. At periods of peak glaciation and ice sheet extent, both would have been drastically impacted. On land this has resulted in considerable extinction, whereby many contemporary habitats were obliterated, and the severe environmental stresses permitted the survival of only a tiny proportion of the preglaciation fauna and flora. By contrast, in the sea, while it is now known that much larger ice shelves extended widely to the point of continental shelf drop-off, patterns of diversity present today indicate that this resulted in extensive fragmentation of marine habitats, rather than outright destruction. This fragmentation provides a classic mechanism that drives the generation of diversity through allopatric speciation—the independent evolution over time of isolated populations of an ancestral line. Although the overall difference between the terrestrial and marine environments is striking, it should be noted that the remnant terrestrial biota, often overlooked as insignificant, does show evidence of analogous radiation processes within the few groups that have persisted.

Few would query the simple statement that Antarctica is an extreme environment, and it is easy to generate physical environmental statistics in support. This leads automatically to the view that Antarctica is stressful. However, it is prudent to avoid anthropomorphism—while conditions are genuinely stressful for humans, they may not be for an organism that has become adapted over evolutionary time to the conditions experienced there. Indeed, such an organism may rapidly experience rising stress levels as conditions move away from those typical of its "extreme" environment towards a state that humans would regard as far more comfortable. Thus Adélie penguins *(Pygoscelis adeliae),* with a circumpolar distribution that is one of the most southerly of all the penguins, show clear indications of heat stress even in the maritime Antarctic at the northern edge of their current range (between the northern Antarctic Peninsula and the South Sandwich Islands). Recent population decreases near the northern edge of this species range may indeed indicate range contraction in part linked with regional climate warming, demonstrating the importance of selection in defining geographical distribution. Over evolutionary time, responses to selection imposed by the Antarctic environment (particularly the abiotic stresses of temperature, extreme seasonality in radiation levels and, on land, low water availability and freeze-thaw cycles) have generated striking examples of the development of evolutionary adaptations. While biotic stresses (largely through competition for resources, or predation) are currently thought to be insignificant and outweighed by abiotic stresses on land (although based on limited data), this is not the case in the much more complex marine communities. Space does not permit an exhaustive survey of relevant studies; rather, a series of illustrations from very different Antarctic biota, environments, and physiological or biochemical processes is considered here.

The challenges of life at low temperature provide clear examples of evolutionary adaptation in the terrestrial realm. Across the continent and the Antarctic Peninsula, virtually all habitats experience the twin challenges of short, cold summers and extended periods of winter freezing. Indeed, some habitats on inland continental nunataks may experience conditions suitable for biological activity for only a few days each year, and not at all in some summers. Studies of Antarctic terrestrial arthropods have revealed two basic adaptive strategies, those of freeze intolerance and freezing tolerance. The former strategy is utilised by the two most common groups of Antarctic terrestrial arthropods, the Acari (mites) and Collembola (springtails). Although the ability is not restricted to Antarctic members of these groups, it is very well developed in these and there is very little evidence of significant cost ("chilling injury") or mortality being experienced before the freezing point is reached, as is the norm in temperate or tropical species. Freezing-tolerant invertebrates are represented in the Antarctic by some higher insects (Diptera, Coleoptera), as well as microscopic invertebrates such as nematode worms. In some freezing-tolerant invertebrates there is also evidence for the use of antifreeze or thermal hysteresis proteins, analogous but with a different evolutionary origin to those found in teleost fish, in stabilising the frozen state.

Water stress, or desiccation, is at least as important as temperature in the biology of most Antarctic terrestrial biota. Desiccation tolerance is of great importance in terrestrial habitats worldwide, and has received considerable attention. The biochemical responses involve the same groups of chemicals as found in freezing tolerance and avoidance, leading to the proposal that desiccation tolerance is likely to have been an evolutionary precursor for cold tolerance in these invertebrates. While cold and desiccation tolerance features are not uniquely associated with Antarctic environments and species, their possession and evolutionary development has clearly been an important factor in the success of the major groups of biota now found in Antarctic terrestrial habitats.

A linked consequence of short, cold, and unpredictable active seasons for terrestrial biota is that it is not normally possible to complete the life cycle within a single season, or even rely on development to a single specific overwintering or resistant stage. Thus, life history features such as obligate diapause and temporally synchronised development, familiar amongst invertebrates of lower latitudes (and even of the milder Arctic terrestrial habitats), are rare or nonexistent. Instead, life cycles often appear to be "free running," and the switch between active and inactive states governed directly by local environmental conditions. This can be seen as Antarctic organisms gaining an evolutionary fitness advantage through the loss of ancestral features. However, extended life cycles per se are not seen as an evolutionary response to the stresses of the Antarctic environment, rather being the result of direct thermodynamic constraints. Indeed, within studies of biochemistry and ecophysiology, there is evidence of evolutionary developments to maximise the rates of biological processes during the short environmental windows that are available for growth and development.

Extended life cycles and slow growth are also typical of Antarctic marine invertebrates and fish. However, endothermic marine vertebrates (birds and mammals) appear to show no such limitation. Considerable populations of birds, seals, and whales are present throughout the Southern Ocean, from the sub-Antarctic islands to the continental coast. While some, notably the great whales and seabirds such as skuas and gulls, migrate to and from the Antarctic annually and thus rely on the region's marine resources only during the austral summer, others are present year-round. The Antarctic coast and pack ice are home to several species of seal (notably, leopard, Ross, and crabeater seals, the latter being one of the most abundant mammals on Earth, in terms of biomass), and virtually unstudied species of the smaller whales. Two penguins (Adélie, emperor) breed around the continental Antarctic coastline, with emperor penguin colonies being virtually restricted to sea ice in this region. Whales, seals, and penguins display clear morphological and physiological adaptations to life in these frigid waters, in terms of particularly effective insulation (blubber, fur, feathers) and control of circulation to surface areas and limbs.

Behavioural and life history adaptations are also present to maximise the chance of breeding success in the short window of opportunity provided during the Antarctic summer. Thus, Adélie penguins commence nesting earlier than any of the other Antarctic penguin species, even at locations where other species breed. Among the mammals, southern elephant and Weddell seals produce some of the richest milk known, and their young show some of the most rapid rates of growth and weaning seen in seals. Perhaps the most spectacular illustration of a life history adaptation driven by Antarctic environmental conditions is that of the life cycle of the emperor penguin. This species, the largest of the penguins living today, is the only vertebrate to spend the Antarctic winter on the continent, or at least the fast ice surrounding it. The short summer is insufficient to permit pairing, incubation, and development and fledging of chicks within a single season. Therefore, egg-laying takes place late in the austral summer, with the egg being incubated on the male bird's feet and protected under a special flap of skin. The female returns to sea after egg-laying and spends the winter foraging. However, the male must remain in the colony, relying on resources of body fat stored during the previous summer. During the most extreme conditions of winter, the incubating male birds obtain some protection from the environment by huddling together in a tightly packed group, with constant movement of individuals away from the windward side, in order to maximise individual survival chances. This is possibly the only example of the complete breakdown of breeding and nesting territoriality known amongst birds. Finally, when the chick hatches later in winter, it is still several weeks before female birds can return with a fresh food supply, and the male provides sustenance in the form of a secretion from its crop. Even then, the timing of the female's return is crucial as, by the end of winter, the male has used such a large proportion of his body's resources that he must also return to the sea to feed. There is a narrow window within which the female must return if the chick is not to be abandoned.

Low temperature presents very different challenges to life in the sea to that on land. The seas around

Antarctica are uniformly cold and, of most biological significance, thermally very stable. Around much of the continent annual variation in sea temperature is less than 2°C–3°C, and, in areas under permanent sea ice or ice shelves, it may be only fractions of a degree. Such stability over geological and evolutionary timescales has allowed biological processes to become tightly matched to their thermal environment, to the extent that any movement away from these stable conditions rapidly exceeds the tolerance limits of the biota. Thus, many Antarctic marine biota exhibit strong stenothermy, with little or no ability to tolerate thermal conditions outside a very narrow band. Such biota are obviously vulnerable to any large-scale process leading to rapid thermal change.

Ice formation is a highly visible seasonal feature of the Antarctic marine environment, with the formation of surface sea ice roughly doubling the apparent area of the continent. However, this represents little threat to biota, unless they become entrapped within it. The formation of anchor ice on substrata in the shallow subtidal environment provides a more direct threat, and is often advanced as an explanation for the apparently low diversity or biomass present in this zone. Antarctic marine invertebrates have body fluids that are isosmotic with seawater (that is, they have the same chemical concentration) and, thus, are not threatened with ice formation unless their medium freezes. This is not, however, the case with fish. Their body fluids are less concentrated than seawater, and therefore in the absence of a protective mechanism would freeze before the freezing point of seawater (~–1.8°C) is reached. Yet fish body fluids are forced to make intimate contact with seawater during passage through the gills, while fish bodies are not insulated from their surrounding medium. This threat has led to the evolution, in Antarctic notothenioid fish, of an antifreeze protein that reduces the freezing point of their body fluids to that of seawater, allowing them to survive by supercooling. Detailed genetic and molecular biological studies have identified the precursor gene for this antifreeze protein, and followed its subsequent modification during the radiation of the notothenioids. Analogous antifreeze proteins are now known from some Arctic fish, with completely different precursors, illustrating the fundamental importance of this adaptation for the existence of teleost fish in polar marine waters.

One group of notothenioid fish, the "icefish," illustrates a further evolutionary adaptation that is unique amongst the vertebrates. These fish have lost the ability to synthesise the oxygen carrying pigment haemoglobin, otherwise ubiquitous across all vertebrates, and their blood contains no functional erythrocytes. That they can do so is a consequence of their cold, stable thermal environment. Oxygen solubility in water is inversely proportional to temperature, and is maximal near to freezing point. However, biological maintenance costs ("standard metabolism") simply increase with temperature, meaning that the cost of staying alive is minimum in seawater near to freezing. Thus, the balance between high oxygen content of Antarctic seawater and low maintenance costs has allowed icefish to dispense with the use of haemoglobin altogether, presumably also generating a significant saving in the costs of protein synthesis.

The high oxygen content of cold seawater has also been proposed to underlie a completely separate evolutionary feature demonstrated repeatedly amongst a range of groups of Antarctic marine invertebrates—that of *gigantism*. Here, high oxygen content of Antarctic seawater represents one extreme of a continuum of availability levels throughout the Earth's oceans (and freshwaters), with levels elsewhere along the continuum generating greater constraints on growth and development.

Finally, it is clear that, as the environmental stresses experienced in Antarctica became more extreme following isolation from the other elements of the Gondwanan supercontinent, they exceeded the thresholds (biochemical, physiological, ecological) beyond which certain parts of the biota (species, higher groups, communities) could no longer persist. This is most striking in the terrestrial environment, where the vast majority of life found is limited to "lower" taxonomic groupings, and most of the "higher" and familiar groups from lower latitudes are simply no longer present. Thus, other than on the Antarctic Peninsula where two flowering plants and two dipteran insects (flies) are found, there are no higher plants (flowering and woody plants), higher insects, nonmarine mammals, or birds, and important ecological functional groups (e.g., obligate grazing animals, predators) are also absent or of little significance. In the sea, diversity patterns also illustrate that environmental conditions have led to reduced overall diversity or loss of some major familiar groups (e.g., reptant decapods—familiar as crabs at lower latitudes—and teleost fish), while others show considerably greater radiation than seen elsewhere (e.g., pycnogonids—sea spiders—and some molluscs). Whether the latter is an evolutionary consequence of reduced competition or the freeing of ecological space by the loss of the former remains debatable. However, a particularly interesting evolutionary example is provided by the remaining representatives of a group that is generally poorly represented—the teleost fish. One group of teleosts, the notothenioids, have survived in southern polar waters, and their subsequent evolution, now confirmed through molecular phylogenetic approaches, provides a particularly clear example of the development of a "species cloud." This example also provides a good example of the importance of the evolution of a novel physiological adaptation (antifreeze protein) at the base of the group's evolutionary radiation.

PETER CONVEY

See also **Adélie Penguin; Antarctic Peninsula; Climate Change; Cold Hardiness; Crabeater Seal; Emperor Penguin; Fish: Overview; Flowering Plants; Gene Flow; Gigantism; Gondwana; Ice Shelves; Insects; Leopard Seal; Microbiology; Molluscs; Nematodes; Parasitic Insects: Mites and Ticks; Penguins: Overview; Ross Seal; Seals: Overview; Seasonality; South Sandwich Islands; Springtails; Temperature; Weddell Seal; Whales: Overview**

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ADÉLIE PENGUIN

Adélie penguin (*Pygoscelis adeliae,* Hombron & Jacquinot 1841) was named after a portion of the East Antarctic coast, Adélie Land, the first known visit to which was made in 1840 by the French expedition led by Jules-Sébastien-César Durmont d'Urville; the region was named after Durmont D'Urville's wife, Adéle. The first specimens of this species were collected there, at Point Géologie, by the two naturalists/surgeons of the expedition, who subsequently described the species. It is one of three species subsequently included in the genus *Pygoscelis,* meaning "rump-legged," in reference to the penguins' upright, bipedal means of walking. The "pygoscelids" are among the few penguins that actually have prominent tail feathers, with the Adélie having the longest, thus earning the alternative name, no longer used, of "long-tailed penguin."

General Characteristics

The Adélie penguin is very much a marine organism, spending about 90% of its life at sea in the waters that encircle the Antarctic continent, not just those lying south of the Polar Front but also those that contain sea ice for at least several months of the year. In the latter, the species differs markedly from its two congeners, the Chinstrap *(Pygoscelis antarctica)* and Gentoo *(Pygoscelis papua)* penguins, which tend to avoid contact with sea ice as much as possible (they breed farther north and nest later in the summer). The Adélie penguin at sea occurs in small flocks, generally five to ten individuals; flock sizes are much larger near to colonies during the breeding season. Throughout the larger part of the year, fall to early spring, these groups spend most of the day resting on ice floes; individuals forage for only a few hours per day. Before spring migration, individuals begin to forage much more in order to build up the fat reserves needed for breeding. Later, in the autumn, at sea, they will forage intensively just prior to their annual moult.

The Adélie is about the same size as the majority of penguin species, about 60–70 cm tall and weighing about 3.2–3.5 kg on average, depending on sex, in its leanest state. However, this species has the important ability to gain body mass by accumulating subcutaneous fat so that at times of the year, just before breeding and just before the annual moult, it reaches a mass of 7 kg among males and 6.5 kg among females. Males are slightly larger than females, perhaps most noticeable in the beak and with greater certainty when the two members of a pair are compared directly with one another. The back and head of the adult in fresh plumage are bluish-black, including the backs of the flippers; its stomach, breast, throat, and flipper undersides are white. The black color quickly loses its sheen, turning to jet-black. By the end of the summer, and just before the annual moult, the plumage has faded noticeably, with tips of feathers then appearing white to brownish. The fledgling and yearling are similar in color pattern, the fledgling of a bluish hue where the yearling is black; both have a white chin, which is lost during the first moult at about 14 months of age. Seemingly, the characteristic long tail of this species is used to increase maneuverability while moving through water usually congested with ice floes and brash.

Populations

Total world population, as of the mid-1990s, is about 2,445,000 pairs, distributed among approximately 161 colonies located on continental headlands and offshore islands. Colony sites are characterized by ice-free terrain, easy access from the sea (not cliffs), lack of persistent fast ice (continuous sea ice locked in place by an irregular shoreline or grounded icebergs), and plenty of small pebbles, which are used as nesting material. Colonies range in size from a few dozen to approximately 200,000 breeding pairs; only six colonies exceed 100,000 pairs. Colony populations are actually about 30%–40% larger than what is represented by breeders, owing to numbers of nonbreeders that spend much time at the colony, generally younger birds gaining initial experience in the breeding process.

In recent decades, breeding colonies throughout most of Antarctica have been increasing in size in response to increasing divergence of sea ice and the size of polynyas, which are areas of minimal ice resulting most often from strong currents or winds. The majority of Adélie penguin colonies occur adjacent to a polynya. More divergent sea ice, perhaps a result of global warming, increases this species' access to the sea and to food. In the very northernmost part of its range, on the northwest coast of the Antarctic Peninsula, sea ice is disappearing and this species is being replaced by its less "pagophilic" congeners. Increasing temperatures may also be providing additional nesting habitat for this species, as coastal glaciers and ice shelves retreat in the north leaving coastal land that was formerly ice covered. The history of this species since the last Ice Age glacial maximum (19,000 years ago) has been one of colonizing sites as ice sheets retreated or as areas of fast ice became less persistent on an annual basis. The portion of the Antarctic Peninsula where the species is now retreating has been occupied only with the lower temperatures and more northerly sea ice that came with the Little Ice Age, which lasted from about 800 years before present until recent years.

Genetically, there are just two forms of this species, one residing in the Ross Sea and the other occurring everywhere else. Although the species exhibits a high degree of philopatry (returning to breed at the place of hatching) under stable and unchallenging conditions, a phenomenon that encourages genetic differentiation, philopatry disappears when heavy sea-ice conditions make it a challenge to return to natal colonies. Such conditions occur sporadically but often enough in local areas that the world population, genetically, is relatively well mixed compared with seabird species elsewhere.

Breeding Biology

Adélie penguins arrive at their colonies to breed beginning in late September at low latitudes (60° S) and by mid-October at high latitudes (78° S). The breeding process then requires about 125 days to complete, with the window of time allowed being slightly longer at lower latitudes. At high latitudes, it is much more critical for penguins to arrive as early as possible. Older birds, particularly males, arrive first. Any bird that arrives at the colony after about mid-November will not breed. Age of first breeding averages about 4.5 years of age (range 3–7) in females and 5.5 years (range 4–8) in males. The proportion of birds that attempt to breed increases with age, reaching maximum, 80%–90%, by age 6 in females and 7 in males. In almost all cases, an individual visits the colony at least 1 year previously before breeding. During that visit, much-needed experience in the breeding process is acquired.

Nests are built of small stones, required to keep eggs above any meltwaters. Nests are grouped into subcolonies that occur on hummocks or ridges, again to avoid meltwater from snow fields or glaciers. Egg laying begins on about 1 November in colonies at low latitude and on 6 or 7 November farther south. Laying is then highly synchronous, with the large majority of eggs laid during a 10-day period. Few eggs are laid in the last week of November. Two eggs are laid in the vast majority of nests, although one egg is common among the very latest layers. As females age, they lay their eggs earlier in the season. Incubation averages about 35 days and involves trade-offs of incubation duties between members of the pair, with males spending slightly more days in that activity. Once the chicks hatch, members of the pair share equally in provisioning chicks.

The newly hatched chick is completely covered in down and weighs on average about 85 g. Parents will guard their chicks, with just one parent foraging at any given time, for the first 22 or so days. The chick then begins to demand additional food, thus driving both parents away. Chicks left alone bunch together in the vicinity of their subcolony in groups called crèches. When parents return with food, giving a loud call upon reaching the nest, chicks will recognize the vocalization and go running to the nest. At 40–45 days, the chick reaches maximum mass, weighing 3.1–3.3 kg, and begins to lose its down to show real feathers. It will fledge, losing about 15% of its mass and becoming independent of its parents, at around 50–55 days of age. Even though the vast majority of females lay two eggs, the average breeding success is about 0.9 chicks fledged per pair that attempt breeding. This figure varies depending on the severity of environmental conditions experienced by the parents.

Following the breeding season, adults undergo a moult of their feathers. The process takes about 2–3 weeks during which they do not enter the water. Thus, they must gorge themselves in the few weeks before moulting, to build up large subcutaneous fat deposits. Most Adélie penguins moult while positioned on large ice floes, but in the northern part of the species' range, where sea ice is not always available, individuals often return to their colonies to moult.

Foraging Behavior

Adélie penguins employ several modes of travel. Over long distances, they swim at about 7–8 km per hour, although in bursts they can swim two to three times faster, being able to dart about almost like fish. Where there is extensive sea ice they walk at about 3 km per hour; pauses in long-range walks translate to a net speed of about 1–2 km per hour. Thus, individuals travel much more efficiently by swimming. This they do, using their flippers for propulsion, by passing underwater, 3–5 m deep, for a couple hundred meters, rising at intervals for a breath "on the fly"; such a behavior is similar to the movement of porpoises and so this mode of travel is called porpoising. When about to make landfall, the frequency of surfacing, actually as they look for places to land, becomes much higher. They also "toboggan" on their bellies over ice, pushing along using their feet; when a stiff breeze is blowing at an angle to their direction of travel (they are virtually "sailing"), they attain speeds faster than walking. When leaving the water to reach the land or ice floes, they accelerate rapidly and are capable of attaining ledges of 2 m above the water surface. Where there are beaches, they walk or scramble ashore.

As a colonially breeding species, Adélie penguins must radiate outward from the colony at sea in search of food. This scenario is known as "central place foraging," and with it the problems of prey depletion or interference competition are important and vary directly with colony size. Therefore, at small colonies, foraging trips may take birds only 10–12 km away, compared with trips on the order of 100 km for birds residing at large colonies or those foraging where food availability is a challenge. Food may become depleted near large colonies.

Throughout most of its range, during the breeding season, the species feeds principally on crystal krill *(Euphausia superba)* and Antarctic silverfish *(Pleuragramma antarcticum)*. In the few areas *(e.g., Antarctic Peninsula)* where continental shelves are narrow and the distance from colonies to the continental slope is near (tens of km), the summer diet is dominated by Antarctic krill *(E. superba)*. Thus, composition of the diet changes depending on the degree to which the penguins are foraging in neritic versus pelagic waters. During winter, individuals dwell away from waters of the shelf at the outer edge of the large-scale ice pack, north of the Antarctic Circle. Here there is an ample period of light each day allowing Adélie penguins to have a diverse diet composed of Antarctic krill, deep-water lantern fish (myctophids, especially *Electrona antarctica*), and squid (especially *Psychroteuthis glacialis*).

In penguins, the duration and depth of diving is directly related to body size. This species is a highly capable diver, being able to hold its breath longer relative to its size than its congeners and most other penguin species, perhaps an adaptation allowing it to forage under vast ice floes where breath holding is an advantage in the search for prey. Foraging dives average 115–230 seconds, with the longest recorded being 350 seconds. Adélie penguins usually feed at 30–60 m depth but have been recorded to 170 m. When foraging during summer to feed themselves and at the same time provisioning chicks, Adélie penguins often dive continuously in bouts lasting 2–4 hours; several bouts often occur sequentially with periods of rest in between before returning with up to 1 kg of food for chicks.

Predators

At sea, Adélie penguins are preyed upon heavily by leopard seals *(Hydrurga leptonyx),* which catch them mainly by stealth, as the penguins are generally capable of eluding the seals in the open water. The seals wait by the edges of ice floes in areas where there are many penguins, or along beaches or benches of beach ice at colonies. They then grab the penguins as they swim by, or as they fall back into the water after failing to attain a high ledge. The seals also smash through thin ice to capture penguins walking overhead. For these reasons, Adélie penguins pause for long periods when they meet an ice crack or lead while walking, or when they are thinking about diving into the water, in order to be confident that there are no seals lurking in the vicinity.

At colonies, skuas (*Catharacta* spp.) act mainly as scavengers, taking eggs and small chicks that are deserted or poorly defended by parents. Once penguin chicks enter into crèches, the skuas are able to kill the smaller and weaker chicks, especially when they become isolated from the crèches or subcolonies. Adult penguins will drive skuas away, not so much in an act of altruism, but in defense of their own chicks or in exercise of a general distaste for the close approach of these birds.

David Ainley

See also **Antarctic: Definitions and Boundaries; Antarctic Peninsula; Birds: Diving Physiology; Chinstrap Penguin; Dumont d'Urville, Jules-Sébastien-César; Fish: Overview; French Naval (*Astrolabe* and *Zélée*) Expedition (1837–1840); Gentoo Penguin; Ice Ages; Leopard Seal; Penguins: Overview; Polar Front; Skuas: Overview; Squid; Zooplankton and Krill**

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ADVENTURERS, MODERN

Adventure Tourism

The term *adventure tourism* defines those activities conducted by nongovernment parties operating in Antarctica—either commercially or noncommercially—for the purposes of physical recreation, exploration, competition, private scientific research, or a combination of any of these. The most common examples from recent times are mountaineering and South Pole ski traverses.

Adventurer Numbers, Locations, and Access

Very few people undertake these activities. For example, in the 2004–2005 season, of 30,232 tourists only 221 were transported inland for the more "adventurous" streams of tourism such as mountaineering and polar ski traverses (IAATO 2005). An even smaller number of climbers and skiers visit the Antarctic Peninsula aboard yachts. Other activities undertaken in recent years include running marathons, sea kayaking, scuba diving, and ballooning.

The principal gateways for Antarctic adventure tourism are Ushuaia in Argentina, Punta Arenas in Chile, and Cape Town, South Africa. The majority of yachts leave from Ushuaia and the majority of tourist flights, either to the Antarctic Peninsula or inland, leave from Punta Arenas. Most of the yachts travel a certain distance down the peninsula, undertaking climbing, skiing, kayaking, wildlife watching, photography, diving, or any combination of these, their itineraries largely defined by time available and sea-ice conditions. Flights from Punta Arenas go to either King George Island or a summer-only base at Patriot Hills in the southern Ellsworth Mountains. From Patriot Hills expeditioners are flown either to Vinson Massif and environs for climbing, or to various starting points for South Pole ski traverses.

History of Adventure Tourism

The first major modern private expedition—and still perhaps the most serious in its technical preparations and scientific contributions—was the Transglobe Expedition led by Sir Ranulph Fiennes from 1979 to 1982, the goal of which was to circumnavigate the

Earth in a north–south direction while passing over both Poles. For the Antarctic section, a party of four wintered in Dronning Maud Land, not far from South Africa's SANAE base, following which—from October 1980 to January 1981—Fiennes, Charlie Burton, and Oliver Shepard crossed the continent using snow scooters with air support, travelling some 2,800 miles. During this time Ginny Fiennes ran the base camp and conducted very-low-frequency radio research.

The longest Antarctic traverse of any kind was the 1989–1990 International Trans-Antarctic Expedition in which six members, including Will Steger (US), Jean-Louis Etienne (France), and Geoff Somers (UK), journeyed by dogsled, with resupply by air, from the northern tip of the Antarctic Peninsula to the then-Soviet base Mirny on the coast of East Antarctica—3,741 miles in 222 days.

The longest full ski traverse was undertaken in 2000–2001 by Norwegians Rolf Bae and Erik Sonneland, who traveled 2,350 miles from the Norwegian base Troll to Ross Island via the South Pole in 107 days, before leaving the continent by ship. Other notable efforts through the recent decades included the "Footsteps of Scott" expedition led by Robert Swan and Roger Mear in 1985–1987, the unsupported journey of Fiennes and Michael Stroud in 1992–1993, and the ski and sail traverse by Alain Hubert and Dixie Dansercoer in 1997–1998.

Commercial ascents of Vinson Massif began in 1985–1986, and by the end of the 2004–2005 season around 970 individuals had climbed to the summit. The main factor for Vinson's increasing popularity is its status as one of the "Seven Summits"—the highest peak on each continent. The success rate for climbers has usually been around 95%, owing to the straightforward nature of the climbing and the generally reliable weather in the area. The first ski descent from the summit of Vinson Massif was made by Martyn Williams (UK) and Pat Morrow (Canada) in 1985, the first snowboard descent by Stephen Koch (US) in 1999, and the first parapente descent by Vernon Tejas (US) in 1988 (Gildea 1998).

On the Antarctic Peninsula and adjacent islands many of the significant peaks were first ascended by personnel from government programs. The area has, however, proved popular with adventure tourists since the 1980s, mainly due to its relative low cost and accessibility for an Antarctic destination. Most of these have traveled by yacht, many undertaking mountaineering and skiing, particularly in areas close to the coast, for reasons of logistics and weather. In recent years the area and peaks around Wiencke Island, Port Lockroy, Paradise Harbor, and the Lemaire Channel have been particularly heavily visited.

Since the early 1990s some significant climbing has been done in the various massifs of the Sor Rondane and Muhlig-Hoffman Mountains in Dronning Maud Land, usually accessed by flights from Cape Town to a blue-ice runway within sight of the mountains. Many of the expedition objectives here are extremely steep rock peaks that have produced the hardest technical climbing yet done in Antarctica.

The other main adventure activity in Antarctica is skiing to the South Pole from one of a number of different starting points, usually close to a coastline, either inside or outside an ice shelf, with the merits of various parameters and styles a highly contentious topic within the adventure community. Expeditioners haul sleds containing their food, fuel, and equipment, sometimes resupplied at one or more points during their journey.

Solo Adventuring

Perhaps the most significant feat of solo adventuring to date has been the Norwegian Borge Ousland's continental crossing, when he traveled 1,760 miles in 64 days without resupply, from Berkner Island to Ross Island, obtaining great benefit from the use of sails, covering 140 miles in one 24-hour period. In the 1992–1993 season his fellow Norwegian Erling Kagge became the first to ski solo to the Pole, a feat that has since been repeated numerous times from various starting points. The current fastest time for a non-kiting traverse from any coast to the Pole was achieved in the 2003–2004 season when Briton Fiona Thornewill traveled unsupported from Hercules Inlet to the Pole in 42 days.

Several significant solo climbs have been achieved, particularly in the Sentinel Range. The most noted of these were the American Terrence "Mugs" Stump's climbs of the southwest face of Mount Gardner (4587 m) and the more difficult west face of Mount Tyree (4852 m) in November 1989. The only major Antarctic peak to have received a winter ascent is Mount Erebus, climbed solo by British alpinist Roger Mear on June 7, 1985.

Regulation

There is currently no legal framework to enforce liability for costs incurred by national Antarctic programs in emergency rescues of private adventurers, a potential problem that has long been a prime concern for governments. To date there have been few such incidents, but all have had some impact on official programs.

All adventurers are strongly advised to take out suitable insurance policies to cover rescues and emergencies, but there is no legal framework in any country to realistically enforce this other than by withholding of permits or prosecution of those who flout the law. In reality enforcement currently relies on cooperation by those operators, particularly those who are members of the International Association of Antarctic Tour Operators, who transport the expeditioners to the continent. Such tourist operators are bound by the 2005 Liability Annex to the Antarctic Treaty to hold suitable insurance to cover liability in the event of causing environmental damage in the course of their activities.

Those adventurers not operating primarily within one of the regular programs of such operators, and whose nations are members of the Antarctic Treaty, are bound by the relevant domestic legislation of their country to give advance notice of their activities, submit an Initial Environmental Evaluation, show significant self-rescue or appropriate third-party search-and-rescue arrangements including insurance, and obtain permits for waste management and import of certain materials.

DAMIEN GILDEA

See also **Antarctic: Definitions and Boundaries; Antarctic Peninsula; Antarctic Treaty System; Aviation, History of; King George Island; Protocol on Environmental Protection to the Antarctic Treaty; Ross Island; South Pole; Tourism**

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AEROBIOLOGY

Aerobiology is the study of finely divided suspensions of particles of biological origin, or activity, in air. The passively airborne materials, which constitute bioaerosols, include microorganisms, pollen, spores, and fragments, or products of larger organisms. They occupy the size range circa 0.5–100 microns (aerodynamic diameter) and are collectively termed the air-spora. Aerobiology encompasses study of the physical, chemical, and biological properties of the air-spora, including the identity, source, movements, survival, infectivity, toxicity, and allergenicity of particles.

The Antarctic air-spora is characterized by low particle abundance and diversity, with a virtual absence of pollen. The density of the Antarctic air-spora (usually <1 particle m^{-3}) is tens or hundreds of thousands times lower than in temperate regions. Numbers of airborne particles are lower during winter than in summer, because of reduced biological activity at this time and the covering of sources by snow and ice. Abundance and diversity of the air-spora is higher in the maritime Antarctic (Antarctic Peninsula, South Shetland Islands, and South Orkney Islands) than in ice-free coastal regions of continental Antarctica, reflecting regional differences in biodiversity. Common particles include lichen soredia (vegetative propagules), feather fragments, and diatoms. Absolute peaks in abundance and diversity occur when air from South America passes over the Antarctic Peninsula and Scotia Arc region. On these rare occasions, the air-spora is more typical in composition to that of temperate regions, having a high content of spores of decomposer fungi and pollen, although abundance remains low in comparison.

The term *aerobiology* was coined in the 1930s by Fred C. Meier, whose work on long-distance spore dispersal included trans-Atlantic and Arctic flights by Charles Lindbergh. However, aerobiological research predates this time, and the first Antarctic studies were conducted by scientists on national expeditions early in the twentieth century: Erik Ekelöf on the Swedish South Polar Expedition, 1901–1904; Hans Gazert on the German South Polar Expedition, 1901–1903; and J. H. Harvey Pirie on the Scottish National Antarctic Expedition, 1902–1904. These workers simply exposed petri plates to the atmosphere, most of which produced no cultures. Similar microbiological studies were conducted by Edward Atkinson on Robert Falcon Scott's last expedition (1910–1913), Archibald McLean on Douglas Mawson's Australasian Antarctic Expedition (1911–1914), and Paul Siple on Richard Byrd's 1933–1935 expedition.

Since the 1960s, aerobiology has been applied to ecological problems and used as a method for monitoring human impacts in Antarctica. Monitoring was initiated in tandem with the Dry Valleys Drilling Project and other US field activities, including testing for biological exploration on Mars and associated quarantine measures. Ecological questions approached using aerobiology concern the dispersal of organisms into and around Antarctica, with particular respect to their colonization of new habitat. This is based on the premise that much of the diversity seen in Antarctic terrestrial and freshwater habitats in present times has arrived in Antarctica since the end of the last major glacial advance. Many of these organisms have small propagules easily carried by the strong winds found in Antarctica. Wind provides one of the few means available for transport of organisms to new habitat, exposed or formed as a result of changes in climate.

William A. Marshall

See also **Australasian Antarctic Expedition (1911–1914); Biodiversity, Terrestrial; Biogeography; British Antarctic *(Terra Nova)* Expedition (1910–1913); Climate Change Biology; Colonization; Exobiology; Fungi; German South Polar *(Gauss)* Expedition (1901–1903); Lichens; Mosses; Scottish National Antarctic Expedition (1902–1904); Swedish South Polar Expedition (1901–1904)**

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AIR-BORNE ICE

Ice forms in the atmosphere when water vapour freezes. Air temperatures generally fall with increasing altitude in the lower atmosphere. The air temperature is 0°C at an altitude of about 2300 m and falls to –56°C at an altitude of 11 km. This means that water vapour should freeze throughout much of the lower atmosphere, and ice crystals should be anticipated at altitudes above approximately 2300 m. Clouds at midaltitudes (3–7 km) contain significant quantities of ice crystals and variable amounts of water vapour, whereas clouds at high altitudes (7–11 km) are entirely composed of ice crystals. Rising air masses expand and cool, and produce clouds of water droplets at higher levels. Water droplets form around the many hundreds of small particles, or aerosols, that are found in air. These particles have diameters that are usually between 0.01 and1 μm. Water droplets in the atmosphere do not readily freeze, and temperatures usually need to fall at least to –5°C to –10°C, and often below –20°C, before ice crystals form. Freezing is brought about when the water droplets come into contact with certain types of aerosol rock particles and organic matter that have the right surface characteristics for water to freeze onto. These types of aerosol are only a small percentage of the total aerosol. Temperatures need to reach approximately –40°C before ice crystals can form directly from water vapour in very clean, or aerosol-deficient, air masses. Once the ice crystal forms, it can grow rapidly from other supercooled water droplets or water vapour. They stop growing when they become so big that they start to fall out of the atmosphere. For example, an ice crystal with a diameter of 75 μm drops at a rate of 5 cm/s, and so can continue to grow for some time before it sinks to a lower, warmer altitude.

Ice crystals come in many shapes and sizes depending on temperature and the amount of water vapour or supercooled droplets in the vicinity of the growing crystal. Ice crystals are usually shaped like columns or plates. Columnar crystals, such as needles, usually form at temperatures between –4°C and –10°C. Plates form between –10°C and –20°C. Plates are flat, thin slivers of ice that fall to earth in a wide variety of shapes. They are typically 5 mm or more in diameter, but they are less than 0.1 mm thick. Columnar crystals form again at lower temperatures, between –20°C and –35°C. Columnar crystals fall with their long axes nearly vertical, whereas plate crystals fall with their flat faces almost horizontal.

Ice crystals in the atmosphere reflect and bend, or refract, sunlight, creating optical effects in the sky, which include solar haloes and sun dogs. Halos are rings of light surrounding the sun. Most halos are bright white rings, but some are coloured because the ice crystals act as prisms, splitting white light into its different colours. Halos are produced by ice crystals in cirrus clouds at altitudes between 5 and 10 km. Halos are often produced by columnar crystals, which fall in a predominantly vertical orientation. Light enters one side of the columnar ice crystal and exits through another side. The light is refracted both when it enters and again when it leaves the ice crystal. The two refractions bend the light by 22° from its original direction. Someone looking at the sun through a cirrus cloud will see a ring of light from the sun or moon. This so-called 22° halo is the most common type of solar halo observed, and can also be seen around the moon for the same reason. Halos also form by crystals that form in very cold weather (below –40°C) at ground level, called diamond dust, and when the sun is close to the horizon.

A rarer observation is a tangent arc, which is a patch of bright light observed along a halo. This occurs when sunlight is refracted by columnar ice crystals whose long axes are oriented horizontally.

Sun dogs are also seen frequently in Antarctica, particularly on cold sunny mornings or evenings. Then, the sun is near the horizon, on the same horizontal plane as the observer, and the air is loaded with ice crystals. Sun dogs, also known as mock suns or parhelia, are brightly coloured spots on each side of the sun. They are seen when platelike ice crystals fall with their flat faces horizontal. Haloes are observed if the plate crystals are randomly oriented, and sun columns are observed if the horizontal crystals gently rock during their fall.

MARTYN TRANTER

See also **Antarctic Ice Sheet: Definitions and Description; Clouds; Ice–Atmosphere Interaction and Near Surface Processes; Meteorological Observing; Precipitation; Temperature**

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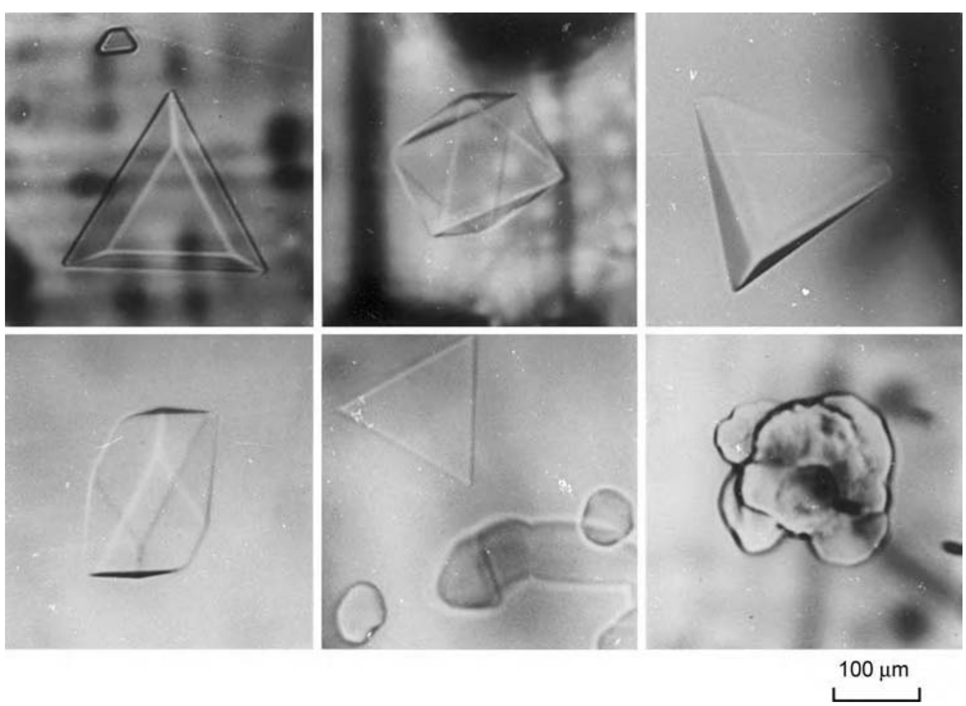
AIR HYDRATES IN ICE

An air hydrate is a transparent crystal in which air constituent gas molecules are trapped in polyhedral cages formed by hydrogen-bonded water molecules.



Air hydrates in ice.

This cage structure is called a clathrate and air hydrates are sometimes called clathrate hydrates. However, such terminology and explanations are misleading because the gas composition of atmospheric air is not preserved in air hydrates found in ice cores recovered from the Antarctic or Greenland ice sheets. Air hydrates found in ice cores contain a large variety of gas composition. An air hydrate might be defined more rigorously as a gas hydrate produced by the reaction of atmospheric air with ice (or water).

The history of natural air clathrate hydrates occurring in polar ice sheets started in the first deep core drilled through the ice sheet to bedrock at Byrd Station, Antarctica (Gow and others 1968). It was revealed that air bubbles completely disappeared below 1200 m depth, raising a puzzle on the existence of air constituent gasses in deep ice sheets. Miller (1969) explained this fact theoretically as a transformation of the air bubbles into air hydrates under high pressures that exceeded the air hydrate dissociation pressure at the *in situ* temperatures. Air hydrate inclusions were first observed by Shoji and Langway (1982) in deep ice samples recovered at Dye-3, Greenland. Further optical microscope examinations of available deep ice cores from Antarctica and Greenland supported Miller's predictions, but revealed an anomalously long transition zone, in which air bubbles and air hydrates coexisted much deeper than Miller's theory suggested. The transition zone in Antarctica is roughly from 500 m to 1200 m. The transition time in Antarctica is several tens of thousands of years. This very long transition is attributed to a very low nucleation rate of air hydrate in ice sheets.

In the transition zone, extremely high levels of gas fractionation were found (Ikeda et al. 1999). Air hydrates in the transition zone have gas compositions enriched by O_2 while N_2 is enriched in air bubbles in the zone. This phenomenon is explained by a faster diffusion (through the ice crystal lattice) of O_2 than N_2 in diffusive mass fluxes from air bubbles to air hydrates in the zone. Careful attention is therefore required in the interpretation of gas composition data obtained from high resolution gas analyses of ice cores.

After recovery of ice cores from deep ice sheets, air hydrates gradually dissociate to air bubbles during cold room storage of ice cores. The dissociation rate strongly depends on storage temperature (50% dissociation after about 4 years at –20°C, yet only 1% dissociation after about 6 years at –50°C).

TAKEO HONDOH

See also **Antarctic Ice Sheet: Definitions and Description; Atmospheric Gas Concentrations from Air Bubbles; Ice Chemistry; Ice Core Analysis and Dating Techniques; Isotopes in Ice**

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AIRCRAFT RUNWAYS

There are no conventional runways on the mainland of Antarctica, and only three on offshore islands. The reason is that less than 0.4% of the total area of Antarctica consists of bare ground (Fox and Cooper 1994). The rest is ice and snow. However, vast areas of the ice sheet are usable by ski-equipped aircraft, and about 1% consists of bare ice that may in places be good for landing unmodified wheeled aircraft. In a few places, seasonal fast ice (sea ice attached to the coast) can be used by even large wheeled aircraft, if the ice is thick enough and snow is cleared from the runway.

Active Runways on Bare Ground

These are made of compacted gravel or crushed rock. Even the longest is too short for large jet aircraft. There are three:

1. Teniente Rodolfo Marsh Martín on King George Island (62°11′ S, 58°59′ W). Length 1292 m. Operated by Chile.
2. Vicecomodoro Marambio on Seymour Island (64°14′ S, 56°37′ W). Length 1250 m. Operated by Argentina.
3. Rothera on Adelaide Island (67°34′ S, 68°08′ W). Length 900 m. Operated by the United Kingdom.

Possible Runways on Bare Ground

There are places on the continent where hard runways suitable for intercontinental aircraft could be built, but high projected costs and environmental considerations have deterred serious interest. Examples are:

1. Marble Point in McMurdo Sound (77°25′ S, 163°42′ E). A 520 m gravel runway was built in 1957 but is no longer usable. A 3000 m runway could be constructed (Mellor 1988).
2. Davis on Vestfold Hills (68°33′ S, 78°01′ E). A 2000 m runway could be constructed (Shevlin and Johnson 1999).
3. Maitri on Vassfjellet (70°46′ S, 11°44′ E). A 3000 m runway could be constructed.
4. Deception Island (62°59′ S, 60°35′ W) was the site of the first powered flight in Antarctica (November 16, 1928). The runway was bisected by a volcanic eruption in 1969. A 1000 m runway could be constructed.
5. James Ross Island (63°52′ S, 57°55′ W). A 3000 m runway could be constructed.
6. Dundee Island (63°29′ S, 56°14′ W). Light aircraft have landed on raised beach gravel. A 1500 m runway could be constructed.

Runways on Sea Ice

Few are in use because the ice commonly breaks up and drifts out to sea in late spring. Snow is removed by a snow plough or snowblower.

1. McMurdo (77°52′ S, 166°29′ E) has two sea-ice runways intersecting at an angle of 80°. Length 3000 m. Operated by the United States. Aircraft weighing up to 300 tonnes have landed on these runways with ice thicknesses of 2.5 m. Prolonged parking of heavy aircraft in one place can lead to ice failure.
2. Terra Nova Bay (74°41′ S, 164°10′ E). Length 2740 m. Operated by Italy and used for C-130 aircraft on wheels weighing up to 80 tonnes.

Runways on the Ice Sheet

There are three kinds of runways on the ice sheet: blue-ice runways, white-ice runways, and skiways.

Blue-ice runways are naturally occurring, snow-free areas that offer the best hope for landing unmodified wheeled aircraft in Antarctica (Mellor and Swithinbank 1989). Blue-ice runways are in use by heavy jet transport aircraft, and in many places there is no practical weight limit. Using satellite images and aerial photographs, Swithinbank (1991) identified many possible sites. Some would prove suitable for wheeled operations by aircraft up to and including Boeing 747. Which sites these are can be determined only by ground surveys that have not yet been done. Large areas of the continent have not even been reconnoitered. The attraction of a well-chosen blue-ice runway is that construction and maintenance costs are almost nil. There are ice fields with clear approaches and potentially long runways facing into the prevailing wind, while others are dogged by turbulent crosswinds from nearby mountains. In practice the choice of an airfield site involves a compromise between the aviator's ideal and its distance from his intended destination. At one extreme, a near-perfect site may prove attractive for intercontinental operations even if it is 1000 km from the ultimate destination in Antarctica. At the other extreme, a relatively poor site may be attractive because of its proximity to the intended destination.

Unprepared blue-ice runways suitable for heavy wheeled aircraft include:

1. Patriot Hills (80°18′ S , 81°21′ W). Length 3000 m. This is in regular use by an Ilyushin-76TD jet transport weighing up to 170 tonnes.
2. Henriksen Nunataks Blue One (71°31′ S, 08°47′ E). Length 2750 m. This is in occasional use by an Ilyushin-76TD jet transport weighing up to 170 tonnes.
3. Austhamaren Peak (71°41′ S, 26°50′ E). Length 2400 m. Two runways intersect at 60°. Unproven.
4. Queen Fabiola Mountains (71°21′ S, 35°20′ E). Length 2500 m. Unproven.
5. Mill Glacier (85°06′ S, 149°50′ W). Length 3000 m. This is occasionally used by C-130 aircraft on wheels.
6. Odell Glacier (76°39′ S, 159°58′ E). Length 2000 m. This has been used by C-130 aircraft on wheels.

Whereas blue-ice runways are unprepared, white-ice runways suitable for wheeled aircraft range from graded bare ice to compacted snow. These include:

1. Pegasus (77°58′ S, 166°32′ E). Length 3000 m. Operated by the United States. This is in regular use by wheeled aircraft weighing up to 300 tonnes (Lockheed C5B).
2. Novolazarevskaya (70°51′ S, 11°36′ E). Length 2760 m. Operated by Russia. This is in occasional use by an Ilyushin-76TD jet transport weighing up to 170 tonnes.

3. Molodezhnaya (67°41′ S, 46°08′ E). Length 2500 m. Operated by Russia. This compacted snow runway has been used by Ilyushin-76TD aircraft weighing up to 170 tonnes.

Ski-equipped aircraft can land almost anywhere on the ice sheet where the surface is level and where sastrugi (wind-formed irregularities on the snow surface) are no more than about 0.2 m high. Skiways in regular use are groomed by grading (planing) or any other means available; methods range from dragging telegraph poles or anchor chains to running heavy tracked vehicles over the surface. Even manual labor with shovels has been used to prepare skiways for light aircraft. The most-used skiways are:

1. Williams Field (77°52′ S, 167°05′ E). Two 3000 m. skiways intersect at an angle of 80°. Operated by the United States. Used for LC-130 aircraft weighing up to 80 tonnes.
2. Amundsen-Scott South Pole Station (90°00′ S). Length 3000 m. Operated by the United States. Used for LC-130R aircraft weighing up to 80 tonnes.
3. Mirniy (66°33′ S, 93°00′ E). Length 3000 m. Operated by Russia. Used by Ilyushin-14 aircraft weighing up to 20 tonnes.
4. Vostok (78°28′ S, 106°48′ E). Length 3900 m. Operated by Russia. Used by Ilyushin-14 weighing up to 20 tonnes and LC-130 aircraft weighing up to 80 tonnes.

Charles Swithinbank

See also **Aviation, History of; Deception Island; McMurdo Station; Russia: Antarctic Program; South Pole; United States: Antarctic Program; Vostok Station; Wilkins, Hubert**

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ALBATROSS AND PETRELS, AGREEMENT FOR THE CONSERVATION OF

The Agreement on the Conservation of Albatrosses and Petrels (ACAP) is an implementing agreement of the 1979 Convention on the Conservation of Migratory Species of Wild Animals (CMS). CMS is an international agreement that aims to conserve terrestrial, marine, and avian migratory species throughout their ranges. CMS entered into force on 1 November 1983, and as of August 2005 had ninety-one Contracting Parties. Under CMS, parties have an obligation to cooperate and develop agreements for species with an unfavourable conservation status as listed in Appendix II (Article IV).

ACAP aims "to achieve and maintain a favourable conservation status for albatrosses and petrels" (Article II.1). Parties agree to take measures to achieve this objective (Article II.2) and apply the precautionary approach (Article II.3). ACAP also aims to improve the understanding of the conservation status of albatrosses and petrels—including their susceptibility to threats at sea and on land and effective mitigation of those threats.

Conservation of albatrosses and petrels is critical since they are long-lived, mate for life, may fledge a chick only once every 2 years, and have low recruitment rates. They are particularly susceptible to longlining, and by-catch of birds has been a major issue. The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) has been addressing the issue of long-lining and is now involved with ACAP to address these threats.

ACAP applies to the twenty-one recognised albatross species and seven petrel species occurring in the Southern Hemisphere. ACAP is open for signature to all twenty-five Range States (including non-CMS signatories) and regional economic integration organisations (Article XV). ACAP was finalised in Cape Town between 29 January and 02 February 2001 and entered into force on 01 February 2004. Eight of the eleven signatories have ratified ACAP, and all signatories are also Antarctic Treaty Consultative Parties (except the Republic of South Africa) as of August 2005.

The Action Plan forms an integral part of ACAP, and outlines measures necessary for meeting the objectives of the Agreement (Annex 2). These

ACAP-Listed Albatross and Petrel Species

Listed species (old taxonomy)*	New taxonomy†	Common name
Albatrosses		
Diomedea exulans	*Diomedea exulans*	Wandering Albatross
	Diomedea dabbenena	Tristran Albatross
	Diomedea antipodensis	Antipodean Albatross
	Diomedea gibsoni‡	Gibson's Albatross
Diomedea amsterdamensis	*Diomedea amsterdamensis*	Amsterdam Albatross
Diomedea epomophora	*Diomedea epomophora*	Southern Royal Albatross
	Diomedea sanfordi	Northern Royal Albatross
Diomedea irrorata	*Phoebastria irrorata*	Waved Albatross
Diomedea cauta	*Thalassarche cauta*	Shy Albatross
	Thalassarche steadi‡	White-capped Albatross
	Thalassarche salvini	Salvin's Albatross
	Thalassarche eremita	Chatham Albatross
Diomedea bulleri	*Thalassarche bulleri*	Buller's Albatross
	Thalassarche nov. sp. (platei)‡	Pacific Albatross
Diomedea chrysostoma	*Thalassarche chrysostoma*	Grey-headed Albatross
Diomedea melanophris	*Thalassarche melanophris*	Black-browed Albatross
	Thalassarche impavida	Campbell Albatross
Diomedea chlororhynchos	*Thalassarche carteri*	Indian Yellow-nosed Albatross
	Thalassarche chlororhynchos	Atlantic Yellow-nosed Albatross
Phoebetria fusca	*Phoebetria fusca*	Sooty Albatross
Phoebetria palpebrata	*Phoebetria palpebrata*	Light-mantled Albatross
Petrels		
Macronectes giganteus	*Macronectes giganteus*	Southern Giant Petrel
Macronectes halli	*Macronectes halli*	Northern Giant Petrel
Procellaria aequinoctialis	*Procellaria aequinoctialis*	White-chinned Petrel
Procellaria aequinoctialis conspicillata	*Procellaria conspicillata*	Spectacled Petrel
Procellaria parkinsoni	*Procellaria parkinsoni*	Black Petrel
Procellaria westlandica	*Procellaria westlandica*	Westland Petrel
Procellaria cinerea	*Procellaria cinerea*	Grey Petrel

**All species are listed in Appendix II of CMS, with the exception of Diomedea amsterdamensis (Amsterdam Albatross), which is an Appendix I species.*
†*New taxonomy will supersede the old taxonomy upon adoption by the Conference of Parties of the Convention.*
‡Species not recognised by some authorities.
Source: ACAP Home Page, see http://www.acap.aq/acap/acap_species, cited August 2005

ACAP Signatories

Participant	Signature	Ratification
Argentina	19-Jan-04	
Australia	19-Jun-01	4-Oct-01
Brazil	19-Jun-01	
Chile	19-Jun-01	
Ecuador	18-Feb-03	18-Feb-03
France	19-Jun-01	28-Jun-05
New Zealand	19-Jun-01	1-Nov-01
Peru	19-Jun-01	17-May-05
Republic of South Africa	6-Nov-03	6-Nov-03
Spain	30-Apr-02	12-Aug-03
United Kingdom	19-Jun-01	2-Apr-04

Source: ACAP Home Page, see http://www.acap.aq/acap/parties, cited August 2005

measures address (a) species conservation; (b) habitat conservation and restoration; (c) management of human activities; (d) research and monitoring; (e) collation of information; (f) education and public awareness; and (g) implementation (see Article VI; Annex 2).

ACAP is in the early states of its development, hence its conservation outcomes are yet to be fully realised. Australia, the Secretariat, has been a key player in the prompt adoption of ACAP, and hosted the first Conference of Parties (COP 1) in 2004 which was attended by five parties, three signatories, and three Range States. Several observers were present at COP 1 including CCAMLR, the Antarctic Treaty Secretariat, Antarctic and Southern Ocean Coalition (ASOC), and the Scientific Committee on Antarctic

Research (SCAR). At COP 1, ACAP Parties adopted Resolution 1.4, *Criteria to define emergency situations and assign responsibility for action for the Agreement on the Conservation of Albatrosses and Petrels*.

Antarctic Treaty Consultative Parties that are Range States have been encouraged to become signatories to ACAP (ATCM XXVII / IP088 2004). Effective implementation of ACAP still requires the signature of more Range States and their cooperation in the implementation of conservation measures outlined in ACAP and developed at the regular COP.

JANE HARRIS

See also **Albatrosses: Overview; Antarctic Treaty System; Birds: Specially Protected Species; Black-Browed Albatross; Conservation; Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Grey-Headed Albatross; Light-Mantled Sooty Albatross; Northern Giant Petrel; Petrels: Pterodroma and Procellaria; Royal Albatross; Seabird Conservation; Seabird Populations and Trends; Seabirds at Sea; Sooty Albatross; Wandering Albatross; Yellow-Nosed Albatross**

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ALBATROSSES: OVERVIEW

Albatrosses belong to the avian order Procellariiformes and the family Diomedeidae. They are a distinctive group of oceanic birds, characterised by their large size, long wings, and strong, powerful bills. Indeed albatrosses are among the largest flying birds, with wingspans exceeding 3 metres in some species. Large body mass and long, stiff wings combine to make these birds unsuitable for powered and flapping flight. Instead, albatrosses glide and soar upon the winds of the world's oceans.

Generally, albatrosses occur in the cooler oceanic regions of both hemispheres, principally between the latitudes of 30° and 55°. These areas are notable for their high winds, and it is wind, and the effect of winds upon the ocean, that most influences the distribution of albatrosses. Albatrosses originated in the Southern Hemisphere some 50 Ma, before spreading to the North Pacific Ocean. Despite a strong fossil record in the Northern Hemisphere, the Southern Ocean is today the stronghold of these birds, with most species confined to southern latitudes.

The name "albatross" is thought to have derived from the Arabic word *al-qadus,* after the Greek word *kados* (meaning scoop or bucket) that was originally applied to pelicans and later extended to other birds. Spanish and Portuguese seafarers later applied the name *alcatraz* to albatrosses and other large seabirds. Albatrosses have held a long fascination for mariners, typified in Samuel Taylor Coleridge's *The Rime of the Ancient Mariner,* perhaps the most familiar depiction of the albatross in Western literature. The albatross slain by the Ancient Mariner is thought to be one of the dark-plumaged and relatively small sooty albatrosses, one of the most diminutive members of the albatross family.

The exact number of extant albatross species is widely debated, as the taxonomic history of albatrosses is both complex and controversial. A revision of albatross systematics in the 1990s based on molecular studies elevated the number of species of albatrosses from fourteen to twenty-four. The acceptance of this revision has been equivocal with some authorities adopting the full twenty-four species, and others advocating a more conservative twenty-one species. The scientific nomenclature used here follows that endorsed BirdLife International, a group that recognises the suite of twenty-one species separated into four genera in the albatross family.

The status and trends of albatross populations are well documented. These assessments have highlighted the globally threatened status of this group of iconic birds, with nineteen of the twenty-one species listed as globally Threatened and the remainder Near Threatened. The precarious survival prospects for albatrosses places them as the avian family most threatened with extinction.

Species Characteristics and Status

The great albatrosses have among the largest wingspans of any flying bird and form the genus *Diomedea,* comprising six species of these massive and spectacular birds. The wandering albatrosses *(D. exulans)* have a wing span of over 3 metres, with body masses exceeding 10 kg. These spectacular birds have a circumpolar foraging distribution and breed at six main island groups in the Southern Ocean. Typically these majestic birds have plumage of variable colour that whitens with age.

The plumage of the Endangered Tristan albatross *(D. dabbenena)* is similar to that of wandering albatrosses, but Tristan albatrosses are much more restricted in their range, with the breeding population essentially restricted to Gough Island (Tristan da Cunha) and birds foraging mainly in South Atlantic waters. The Antipodean albatross *(D. antipodensis),* is endemic to New Zealand, and is listed as Vulnerable as it is restricted to three small islands for breeding. At sea, these birds disperse across the Tasman Sea and South Pacific Ocean, including areas of the Southern Ocean. Whilst smaller than wandering albatrosses, both species have a similar juvenile plumage, with Antipodean albatrosses retaining a darker adult plumage. This character is more similar to the Amsterdam albatross *(D. amsterdamensis),* which also retains a darker adult plumage. Amsterdam albatrosses are classified as Critically Endangered as the species comprises only an extremely small population (estimated at eighty mature individuals) confined to a single breeding island. Little is known about the foraging distribution of these imperilled birds, although breeding birds are known to forage over 2000 km from their breeding site of Amsterdam Island in the Indian Ocean.

The remaining two species of *Diomedea* albatrosses are the Southern Royal *(D. epomophora)* and Northern Royal *(D. sanfordi)* albatrosses. These species have broadly similar plumage patterns, although they differ with respect to underwing patterns and extent of white on their backs. Both species are listed as Threatened as a result of their restricted breeding ranges, the Northern Royal albatrosses being more acutely threatened (listed as Endangered) as a result of poor breeding success that is likely to sustain significant population decreases in the future.

The most numerous and frequently observed albatrosses in the Southern Oceans are members of the nine species that comprise the genus *Thalassarche*. Collectively these smaller albatrosses were known as mollymawks, from the Dutch word *mallemok,* which literally means "foolish gull." These birds are smaller than the great albatrosses, with wingspans of about 2 metres and average body masses of 2–4 kg. The plumage patterns of this group of albatrosses are broadly similar with light underparts, dark upperwings and grey or white heads.

The black-browed albatross *(Thalassarche melanophris)* is the most numerous of all albatross species and breeds at twelve sites around the Southern Hemisphere. Despite a current population of 680,000 pairs, as a result of documented population decreases this species is listed as Endangered, as it is inferred that the population decreases will continue to diminish the population. The morphologically similar Campbell albatross *(T. impavida),* distinguished from black-browed albatrosses by its pale iris, is globally listed as Vulnerable as the species is effectively restricted to a single New Zealand sub-Antarctic island.

The grey-headed *(T. chrysostoma)* and Buller's *(T. bulleri)* albatrosses are generally similar in their plumage with grey on their heads and necks; their bills are black with striking yellow to red stripes. Both species are listed as Vulnerable, Buller's albatrosses because of their restricted New Zealand breeding distribution and grey-headed albatrosses because of population decreases that, if they persist, will result in the Threatened status being upgraded to Endangered.

The Indian yellow-nosed albatross *(T. carteri)* and Atlantic yellow-nosed albatross *(T. chlororhynchos)* also have the striking beak colouration, but have paler heads than the grey-headed and Buller's albatrosses. Both species are listed as Endangered as a result of observed population decreases, although the Atlantic yellow-nosed albatross may require reclassification to Critically Endangered if threats do not abate.

The largest of the *Thalassarche* albatrosses are the shy *(T. cauta),* Salvin's *(T. salvini),* and Chatham *(T. eremita)* albatrosses, characterised by their deeper, yellow to grey bills, their predominantly pale underwings, and their relatively larger size. A white forehead and crown bordered by a dark eyebrow common to this group of birds presents them as looking rather stern! The Threatened status of these birds, which all breed exclusively in Australia and/or New Zealand, varies, the shy albatross listed as Near Threatened, Salvin's albatross as Vulnerable, and the Chatham albatross as Critically Endangered. Recent molecular and morphological information suggests that the Australian and New Zealand populations of shy albatrosses are distinct, and could represent separate species.

The remaining two species of albatross that traverse the Southern Ocean are the small and dark *Phoebetria* species, the sooty *(Phoebetria fusca)* and the light-mantled sooty albatross *(Phoebetria palpebrata).* The distribution of these two species differs, with sooty albatrosses being more restricted and also less numerous than the light-mantled sooty albatross, which has a circumpolar breeding distribution. As a result of available information on population trends, the light-mantled sooty albatross is listed as Near Threatened, while the sooty albatross is listed as Endangered. However, less is known about these species, compared with other albatrosses, and more contemporary population data may result in revision of their conservation status.

The remaining four species of albatross in the family Diomedeidae belong to the genus *Phoebastria.* The waved *(P. irrorata),* short-tailed *(P. albatrus),* Laysan *(P. immutabilis),* and black-footed albatross *(P. nigripes)* differ markedly in many elements of their appearance, biology, and behaviour. The waved albatross breeds only in the Galapagos Islands, whilst the Laysan and black-footed albatrosses are typically birds of the North Pacific Ocean, breeding on islands of the Hawaiian Leeward Archipelago and Japan. The short-tailed albatross is the biggest of the North Pacific species and is restricted to breeding on small isolated islands in Japan, principally the volcanic island of Torishima.

Distribution and Habitat Use

Albatrosses are among the most oceanic of all seabirds and, except whilst breeding, rarely approach land. Knowledge of the oceanic distribution of these birds has been derived in the past from at-sea surveys and returns of banding records. In more recent years, the ability to track albatrosses by satellite and archival geolocation tags has revolutionised our understanding of the incredible journeys that these birds undertake. Many species travel thousands of kilometres on trips between incubation shifts, or between feeding chicks. During the nonbreeding season, some species undertake complete circumnavigations of the Southern Ocean, one grey-headed albatross recently achieving this feat in just 46 days. While the high seas are the realm of many of these birds, they are consistently attracted to areas of the ocean that combine bathymetric and hydrographic features that provide important feeding areas. Some species show a propensity for aggregating in areas coinciding with frontal systems and mesoscale oceanographic features, whereas others, such as the shy albatross, forage preferentially in continental shelf and slope waters.

The diversity in foraging distributions of albatrosses is only recently becoming apparent as studies are able to compare not only different species during different phases of the breeding cycle, but also different sex and age classes and birds from different colonies. Understanding the oceanic distribution of these birds remains of considerable importance not only for identifying areas of overlap with environmental features but also with respect to elucidating overlap and interactions with fishing operations, and the recognition of areas can be incorporated in the identification of marine protected areas.

In the Southern Hemisphere, albatross breeding colonies are almost exclusively located on remote and windswept offshore islands between 37° and 57° S. The nesting habitats of these birds vary, with the larger great albatrosses nesting in dispersed groups on flat or gently sloping ground. The smaller *Thalassarche* albatrosses have a more varied nesting habitat that includes bare exposed rock flats and slopes, tussock slopes, or ledges on cliffs or steep slopes. Reflecting the variety of terrestrial habitats that these birds occupy, some species such as Buller's albatross nest in areas as diverse as meadows, tussock-covered slopes and cliffs, and under the canopy of forests. The two *Phoebetria* species nest on precarious ledges of steep cliffs, this habit perhaps explaining our relatively poor understanding of the life history of these species.

Life History

Albatrosses are characterised as having long life spans, low rates of natural mortality, high recruitment rates, and low productivity. Indeed it is their extreme life history traits that make them so vulnerable to influences that increase their natural levels of mortality. The breeding cycle of some of the great albatrosses is extremely long, extending over 12 months from nesting to chick fledgling, resulting in a biennial breeding pattern where breeding, if successful, can be attempted only every 2 years. Other smaller albatross species, such as shy and black-browed albatrosses, are able to breed in successive years, allowing an annual cycle. However, the *Phoebetria* species and some *Thalassarche* albatrosses are able to breed within a 12-month period yet breed only every 2 years.

All albatrosses lay a single egg, with southerly species constructing a large bowl-shaped nest and more tropical species laying in a simple scrape. The egg is incubated by both parents in alternating shifts for 6–12 weeks, after which the chick takes 3–9 months to fledge, depending on the species. Following fledging, albatrosses remain at sea for 3–5 years before returning to their natal island to breed. Albatrosses begin to breed at about 6–12 years of age, and generally retain the same partner between breeding attempts. Albatrosses are long lived, and have been known to breed when approaching 60 years of age. Life history models suggest that a few birds may live in excess of 80 years.

Diet and Trophic Interactions

Albatrosses are included among the oceans' top predators and scavengers. As with other Procellariiformes, albatrosses are characterised by having external tubular nostrils on the upper bill, these generally being associated with well-developed olfactory systems. An acute sense of smell is used by albatrosses to detect food, in addition to visual cues to detect prey and other predators. Most albatrosses are predominantly diurnal feeders, although some smaller species are also active at night, especially during periods of full moon. The larger albatross species are typically surface feeders, but the smaller species are able to dive several metres and actively propel themselves underwater. Albatrosses are generally described as being opportunistic feeders, their prey including squid, fish, and crustaceans. They are both active foragers, catching live prey, and also scavengers, taking advantage of dead prey and fishery offal, discards, and baits. Though albatrosses are generally solitary while searching for prey, when a rich food source is detected, multispecies flocks of hundreds of birds will congregate in efforts to obtain food.

It is this propensity to scavenge and congregate behind fishing vessels that threatens the survival of many albatross species today. The catastrophic population decreases recorded for albatross populations recently are mainly a consequence of incidental mortality in longline and trawl fisheries. More than 300,000 seabirds, including an estimated 100,000 albatrosses, are believed to be killed on longlines each year. Of the twenty-six species of seabird in danger of extinction because of the deaths caused by long-lining, seventeen species are albatrosses. Concerted and coordinated actions at both local and international levels are required to reverse the decrease and potential demise of these magnificent seabirds.

ROSEMARY GALES

See also **Amsterdam Albatross; Amsterdam Island (Île Amsterdam); Black-Browed Albatross; Gough Island; Grey-Headed Albatross; Light-Mantled Sooty Albatross; Royal Albatross; Seabird Conservation; Seabird Populations and Trends; Seabirds at Sea; Sooty Albatross; Southern Ocean; Wandering Albatross; Yellow-Nosed Albatross**

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ALFRED WEGENER INSTITUTE FOR POLAR AND MARINE RESEARCH, GERMANY

The Alfred Wegener Institute for Polar and Marine Research (AWI) was established as a public foundation in 1980. It is a member of the Helmholtz Association of German Research Centers (HGF).

AWI is the national coordinator of German polar research activities. As an interdisciplinary scientific institution, AWI performs top-rate polar and marine research in strategic programmers of great complexity with large-scale facilities and infrastructure including the operation of mobile and stationary research platforms in the Arctic and Antarctic. It provides advice to the German government in Antarctic-related affairs.

Within the international organizations on polar and marine research, AWI represents the interests of German research institutions and the Federal Republic of Germany. It provides members for the international committees and organizations of the Antarctic Treaty System such as the Scientific Committee on Antarctic Research (SCAR), the Council of Managers of National Antarctic Programs (COMNAP), and others. Jörn Thiede, director of AWI, was elected as the president of SCAR for 2002–2006. AWI also holds membership in the European Polar Board (EPB), an associate committee of the European Science Foundation (ESF), the International Arctic Science Committee (IASC), the UN Intergovernmental Panel on Climate Change (IPCC), and other relevant organizations on Arctic research (AWI 2002; AWI 2004).

Several AWI scientists have had leading roles in past and present activities of international cooperative programs, including European Project on Ice Coring in Antarctica (EPICA), Climate Variability and Predictability (CLIVAR), Global Ocean Ecosystem Dynamics (GLOBEC), Joint Global Ocean Flux Studies (JGOFS), and others.

Since 1980, the main headquarters of AWI has been located in Bremerhaven. After the unification of Germany a newly established research facility in Potsdam became part of the institute in 1992. The Potsdam facility is primarily concerned with geoscientific studies in periglacial regions and with the investigation of atmospheric processes and climate in the polar regions. In 1998, AWI was enhanced by the integration of the Biologische Anstalt Helgoland

The major tool for AWI's marine research, the high-class ice-breaking research and supply vessel "RV Polarstern," commissioned in 1982. It calls the Atka Bay regularly to supply the German Antarctic research station "Neumayer." (Reference: AWI archive 2004)

(BAH), which included merging of the island facilities on Helgoland and on Sylt (Wadden Sea Station). Hence, research on the development and succession of living communities of coastal regions and the investigation of natural secondary products of marine organisms and of inputs of chemicals into the system form an additional focus at AWI.

As of 2005, AWI has 788 employees in Bremerhaven, Potsdam, and on the islands of Helgoland and Sylt. It operates on a budget of approximately 100 million euros and is funded jointly by the German Federal Ministry of Education and Research (90%), by the state of Bremen (8%), and by the states of Brandenburg and Schleswig-Holstein (1% each). External funds are applied for from the Deutsche Forschungsgemeinschaft (DFG), the framework programs of the European Union (EU), and other agencies.

AWI is an interdisciplinary scientific research institution with four departments: geosciences, biosciences, climate sciences, and new technologies. The research covers important components of the Earth system to investigate the oceans' role in global climate and to assess the role of polar regions within the Earth system. Observation and modeling focus on understanding naturally and anthropogenically driven processes of interaction between different compartments of the Earth system and their relevance in global processes with the aim to reduce present uncertainties in assessing future developments of global environmental changes induced by natural causes and human interference.

In this context, the fundamental database is composed of results from scientific investigations on recent variability of oceanographic and climatic processes, assessment of their changeableness in recent geological history, and the reconstruction of the long-term climatic history, which led to the formation of inland ice masses in previously comparatively warm polar regions of the Antarctic and Greenland. The wide spectrum of methods applied to pursue these research goals include modern satellite-based remote sensing as well as deep sea drilling and ice coring. AWI places particular emphasis on investigations of polar seas and their living biota. It undertakes terrestrial polar research and contributes significantly to atmospheric science, and to the paleoclimatic history of subpolar regions with permafrost.

Substantial services and infrastructures have been established such as logistic management of mobile and stationary research platforms, expedition store, laboratories, ice-core storage, aquarium, compute centre and databases networks, and library and electronic Publication Information Centre, as well as public relations department.

The high-class icebreaking research and supply vessel RV *Polarstern* is AWI's most powerful tool in all fields of marine research. Since 1982, it has been one of the most valuable polar research ships in the world. It traveled more than one million nautical miles and completed twenty-three Antarctic and twenty-one Arctic expeditions prior to 2006. Two aircraft Dornier 228-101 are used for scientific and logistic missions in the Arctic and Antarctic. Measurement techniques have been developed for glaciological, geophysical, and meteorological air-borne surveys. The permanently occupied stations in the Antarctic (Neumayer Station) and in the Arctic on Svalbard (Koldewey Station) are designed for long-term running of observatories. Summer-only stations are the Kohnen Station on the inland ice plateau of Dronning Maud Land and the Dallmann Laboratory on King George Island in the Antarctic and the Samoylov hut located in the Lena river delta in Siberia. The fleet of research vessels is completed by RV *Heincke,* facilitating marine investigations in regions from subpolar to tropical latitudes and by four small ships assigned to the island stations on Helgoland and Sylt.

The computer centre provides compute capacity for numerical models, integrated information systems including data storage, and retrieval systems for long-term archives of scientific data from expeditions and laboratories. As of 2006, 20 years of meteorological data from weather observations, radiosonde launches, and solar radiation measurements of the research ships and polar stations were available. Likewise, oceanographic data from flow meters and profile probes can be accessed. Aside from the data holdings of participating institutions there are additional data from over twenty-five national, European, and international projects available on a long-term basis. The Publishing Network for Geoscientific & Environmental Data (PANGAEA) is the platform for one of the few ICSU-approved World Data Centers (PANGAEA 2005). The Polarstern Data Acquisition System (PODAS) archives data collected during the RV *Polarstern* expeditions (PODAS 2005). To date the electronic Publication Information Centre (ePIC) of AWI has 10,700 records with some 7,100 AWI publications and 3,600 others such as posters, patents, and non-AWI publications (ePIC 2005). Any publication search at www.awi-bremerhaven.de will be processed by ePIC even providing the primary data and expeditions, which have been the basis to get the scientific results. State-of-the-art geographical information systems allow the production of charts and maps and the interpretation of geo-referenced data.

Currently, AWI has contractual agreements for scientific cooperation with scientific institution in twenty-three countries. Formal bilateral collaboration agreements for polar and marine research exist with sixty individual foreign research institutions.

On July 15, 1980, AWI was inaugurated and named after Alfred Wegener, an early prominent German polar researcher. He was an experienced explorer and died during his fourth Greenland expedition in 1930. Wegener was a geophysicist, meteorologist, and glaciologist and, in those capacities, not only a great research traveller and observer but also a distinguished theoretician. He developed the first in-depth ideas about the drifting of continents. Because his hypotheses appeared far-fetched at that time, his colleagues met him with hostility. It was not until the 1970s that Wegener's hypotheses were proven correct. In his capacity as expedition leader, Wegener was very highly respected as a person. He was the most appropriate candidate after whom to name Germany's largest polar research institution.

HARTWIG GERNANDT

See also **Antarctic: Definitions and Boundaries; Antarctic Treaty System; Climate; Climate Change; Council of Managers of National Antarctic Programs (COMNAP); Earth System, Antarctica as Part of; Germany: Antarctic Program; Global Ocean Monitoring Programs in the Southern Ocean; Plate Tectonics; Scientific Committee on Antarctic Research (SCAR); Southern Ocean: Climate Change and Variability**

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ALGAE

Algae are the most widespread and diverse photosynthetic organisms in the Antarctic terrestrial ecosystem. Currently, the term *algae* is often applied only to eukaryotic forms, that is, those with membrane-enclosed nuclei, chloroplasts, and mitochondria, to distinguish these from prokaryotic cyanobacteria (commonly known as "blue-green algae" or "blue-greens"), which have a much simpler cell structure. In this account both are regarded as algae as they share possession of chlorophyll and production of oxygen as a by-product of photosynthesis. Moreover, both have a major ecological role as primary producers. There are few habitats receiving light and having a sufficient supply of water and nutrient mineral salts in which the two forms do not co-occur. Algae are remarkably diverse and are the product of about nine distinct major evolutionary lineages. Fungi, plants, and animals have, by contrast, each emerged from a single lineage.

Algae grow in aquatic and nonaquatic habitats. The former includes lakes, ponds, and streams while the latter includes soils and rocks. In nonaquatic habitats, algae become more prominent in the vegetation as the environment becomes more challenging (e.g., with progression south from sub-Antarctic islands to continental Antarctica). However, in aquatic habitats, it is algae that usually dominate the biomass at all latitudes. While this account is about free-living forms, algae are also photosynthetic partners of fungi in the mutually beneficial symbiosis known as lichen in which they extend their range to habitats where otherwise they would be unsuccessful. For instance, only lichens grow on many exposed rock surfaces from sub- to continental Antarctica.

It is impossible to accurately estimate total species numbers of algae in Antarctica because there are few detailed studies of all habitats at localities covering the full latitudinal range. Many identifications are dubious and most have been made using floras produced for temperate regions. Algal taxonomy is undergoing considerable revision from the level of species to class, with increasing application of molecular genetics. An estimate of 700–1000 species in maritime and continental Antarctica might be reasonable while undoubtedly many more occur in sub-Antarctica. The following account focuses on the former regions.

In terms of biomass, blue-greens are dominant, especially at higher latitudes and in more extreme environments. Chlorophyta (green algae) can also be prominent. Among the Heterokontophyta, Bacillariophyceae (diatoms) are important especially in aquatic habitats while Xanthophyceae (yellow-green algae) are frequent in nonaquatic communities. Dinophyta (dinoflagellates), Cryptophyta (cryptophytes), Euglenophyta (euglenoids), and Chrysophyceae (golden algae) are of lower diversity, mostly as phytoplankton.

Algae in Aquatic Habitats

Communities vary greatly in species structure depending on prevailing physicochemical conditions. Lakes are waterbodies in which water is present all year, while ponds either freeze completely in winter or evaporate dry in summer. Streams flow for up to a few months over summer, then melt ceases and algae in stream beds become freeze-dried. The extreme high-amplitude fluctuations in pond and stream environments constrain species diversity compared with that in lakes. Chemical factors of importance in all habitats are availability of nutrients and concentrations of nonnutrient salts. In lakes, light is a significant influence. Light of different intensity and quality penetrates the water column depending on persistence and thickness of surface ice.

Aquatic communities are either periphyton or phytoplankton. The former attach to sediments, rocks, and aquatic vegetation while the latter are suspended in the water of lakes and ponds.

Mats of filamentous blue-greens are almost ubiquitous as periphyton in all aquatic habitats. Simple unbranched filaments of *Phormidium* spp. and *Leptolyngbya* spp. (order Oscillatoriales) are usually dominant while colonial unicells of *Aphanocapsa* sp. and filamentous *Nostoc* sp. can also be abundant. The latter is one of several Antarctic genera of blue-greens able to use elemental nitrogen as a nutrient by nitrogen-fixation in specialised cells termed heterocysts. Mats have varying abundance and diversity of associated diatoms, and unicellular and filamentous green and yellow-green algae.

Diatoms can be particularly diverse. For instance, 234 species have been recorded from freshwater lakes of the South Orkney and South Shetland Islands. However, in the closest known ponds to the South Pole, at La Gorce Mountains (86°30′ S), just one species, *Luticola muticopsis,* was found associated with thin mats dominated by one species of blue-green. Diatoms recovered from lake sediment cores are being used in palaeoecological studies (e.g., Roberts & McMinn 1997).

In streams, coherent mats usually cover much of the bed. However, where stones protrude through the mat, they are coated by black crusts of other blue-greens (e.g., unicellular, colonial *Gloeocapsa* spp. and filamentous *Schizothrix* sp. and *Calothrix* sp.). Unbranched filaments of green algae (e.g., *Binuclearia tectorum*), and yellow-green *Tribonema* sp. can be found trailing downstream from stones to which they are attached. Particularly in maritime Antarctica, stream beds can become covered by green filaments such as *Zygnema* sp. and *Mougeotia* sp. By contrast, in the dry valleys of southern Victoria Land, short narrow ribbons of the dominant green algae, *Prasiola calophylla,* verdantly encrust undersurfaces of stones where they are shaded from intense insolation. At the source of these streams, on meltwater irrigated terminal walls of glaciers, *P. calophylla* can be found caught around irregular protrusions of ice.

Phytoplankton communities are dominated by the smallest unicellular, colonial, and filamentous algae. Small size, ability to move using whiplike flagella, and nonspherical shapes all aid in keeping the organisms in suspension, especially in calm environments such as permanently ice-covered lakes (e.g., Lakes Fryxell and Vanda in southern Victoria Land). Species range from unicellular blue-green *Synechocystis* (1 μm diameter), through diverse unicellular phytoflagellates (e.g., the cryptophyte *Chroomonas lacustris,* the green *Pyramimonas* sp., and the chrysophycean *Ochromonas* sp.) and nonflagellate unicells (e.g., the green *Monoraphidium* and *Ankyra* sp.), to small colonial forms (e.g., the greens *Ankistrodesmus* sp. and *Scenedesmus* sp., which are a few tens of micrometres in diameter).

Certain lakes have particularly notable phytoplankton communities. Deep Lake at the Vestfold Hills never freezes due to its hypersaline waters. The sole phytoplankton is the green flagellate unicell *Dunaliella* sp. This swims even at a frigid winter temperature of –14°C. By contrast, different phytoplankton occupy different positions in the strongly vertically stratified waters of the permanently ice-covered lakes of southern Victoria Land. In Lake Fryxell, *Ochromonas* sp. inhabits cold, fresh, nutrient-poor but well-illuminated water just below the ice while *Chroomonas lacustris* and *Pyramimonas* sp. occur in deep, warmer, saline, nutrient-enriched but poorly illuminated conditions just above anoxic bottom waters. One study records twenty-eight species in the phytoplankton community (McKnight et al. 2000).

Various phytoflagellates (e.g., *Pyramimonas gelidicola, Ochromonas* sp., and *Cryptomonas* sp.) are able to supplement their nutrient and energy supplies by ingestion of particles of organic detritus, bacteria, and the smallest phytoplankton. This ability, in combination with photosynthesis, is termed mixotrophy. In Antarctica, this is beneficial in lakes where mineral nutrients are in low supply and when light is very dim or absent (e.g., in winter, when an alternative supply of organic carbon is needed to replace photosynthesis) (Laybourn-Parry et al. 2000).

Ponds are widespread, numerous, and highly diverse and almost all contain algae. Cryoconite ponds on melting surfaces of glaciers contain windblown mineral particles at the base of cylindrical melt-filled holes in the ice. They can be dominated by colonies of *Nostoc* sp. or contain a diversity of blue-greens and unicellular greens resembling communities in nearby soils. Ponds can cover extensive areas of ice shelves, for instance they extend over 1200 km^2 of the McMurdo Ice Shelf. Mat communities in these are dominated by nine species of blue-greens, six species of diatoms, and unidentified green unicells (Howard-Williams et al., 1990). Ponds in depressions in rocks and mineral soils usually contain mats similar to those on wet soils and close to lake shorelines. In and around penguin colonies, the highly nutrient-enriched waters often support dense populations of phytoplankton such as *Chlamydomonas* spp. and cryptophytes.

Algae in Nonaquatic Habitats

Mineral soils are widespread over ice-free regions. Extensive surface crusts and mats occur where there is a persistent melt-water supply in summer. Filamentous blue-greens *Phormidium* spp. and *Leptolyngbya* spp. are usually dominant. Mucilaginous colonies of *Nostoc commune* are also common. Within the mats are microscopic populations of green algae (e.g., unicellular *Chlorococcum* spp.), diatoms (e.g., *Luticola muticopsis* and *Hantzschia amphioxys*), and yellow-green algae (e.g., filamentous *Xanthonema* spp. and *Heterococcus* spp.).

Even at far south, high-latitude locations in La Gorce Mountains (86°30′ S, 148°00′ W, c. 2000 m altitude) bright green patches of the microscopic filamentous chlorophyte *Desmococcus* cf. *olivaceus* are visible at the interface between glacial ice and an overlying layer of fine-grained morainic detritus where this is just a few millimetres thick. Moisture to support growth is supplied by ice melt when the overlying dark mineral material is warmed by the sun to temperatures up to 7°C. Ambient summer air temperatures here are about –14°C. This is an example of the more general importance of solar heating in provision of a favourable microclimate.

Where water supply is even more restricted, algae are present as microscopic populations. An example is the soil in furrows around ice polygons in southern Victoria Land dry valleys. Here, microscopic populations of unicellular *Botrydiopsis* sp. persist in soil that is moistened by snowmelt, the snow having drifted into the depressions during rare summer snowfall. Even the most arid soils contain algae, which probably have little opportunity for growth but survive for long periods in a desiccated condition.

In the vicinity of bird and seal colonies the composition of soil algal communities reflects the greatly increased input of nitrogenous and phosphatic nutrients derived from the waste products of these marine animals. Luxuriantly green, sheetlike growths of the chlorophyte *Prasiola crispa* cover wet ground where it is not too disturbed by trampling. Although this marine influence occurs predominantly at coastal sites, for instance around penguin colonies, inland nunataks with nesting sites of petrels have the same algal communities. For instance, *P. crispa* is the most prominent alga at Robertskollen (Dronning Maud Land, 71°28′ S, 3°15′ W) despite it being about 130 km from the open sea.

Geothermal soils heated by volcanic activity are of very limited extent in Antarctica, being found close to the summits of three volcanoes in the Ross Sea region, on Deception Island in the South Shetland Islands, and on the South Sandwich Islands. They occur at altitudes up to 3700 m on Mount Erebus, Ross Island. At soil surface temperatures in excess of 35°C a thermophilic cyanobacterium, *Mastigocladus laminosus,* forms dark blue-green crusts. This species is a cosmopolitan thermophile and has probably been dispersed by wind to its isolated Antarctic habitats. At cooler temperatures species of unicellular green algae (*Chlorella* spp., *Coccomyxa* spp., *Bracteacoccus* sp.) dominate.

Soil algae have undoubtedly been transported to Antarctica by humans but whether they have colonised outside research stations is unknown (Broady & Smith 1994).

The living surfaces of bryophytes invariably support epiphytic populations of microscopic algae and small colonies of *Nostoc*. Black, green, and orange crusts of algae often develop over dead moss. Algae communities differ between moss communities. For instance, in the South Orkney Islands, moss turf supports a high abundance of the green unicell *Pseudococcomyxa simplex* while wetter moss carpets support a species rich community of blue-greens, diatoms, and green algae. Moss cushions provide a habitat for a limited flora of large unicellular green algae called desmids, with *Actinotaenium cucurbita* being the only species existing at 77° S in the southern Victoria Land dry valleys.

Algae are often associated with rock and stone surfaces. In moist conditions encrusting growths are visible (i.e., the communities are epilithic). In relatively humid maritime Antarctica crusts of cubical cell clusters of the green alga *Prasiococcus calcarius* form on sheltered faces of coastal rocks. In continental Antarctica, epilithic growths occur only where meltwater percolates over rock surfaces. Here, black crusts are dominated by unicellular, colonial blue-greens such as *Gloeocapsa* spp. The darkly pigmented mucilage coating the cells provides protection from intense insolation in summer and prolongs the period of cell hydration when the water supply ceases.

Where water supply is greatly restricted, algae retreat to hidden, so-called cryptic habitats, where traces of water can be retained. Although biomass is very low, algae in such niches dominate vegetation in the extensive cold deserts, as found in the dry valleys of southern Victoria Land and at the Vestfold Hills. It has been suggested that extraterrestrial life could be discovered in habitats similar to these.

The hypolithic habitat is provided by the undersurfaces of translucent stones, such as quartz. Where stones lie on top of the soil, light can penetrate to moist soil below, even if adjacent surface soil is extremely dry. Vivid crusts of green (e.g., *Desmococcus* spp. and *Prasiococcus calcarius*) and blue-green algae (e.g., *Leptolyngbya* sp. and unicellular *Chroococcidiopsis* sp.) coat the undersurfaces.

Algae and lichens can also exist within translucent rocks. Either they are chasmoendolithic, i.e. in narrow cracks penetrating the rock surface, or they are cryptoendolithic, i.e. in minute pores between rock crystals without obvious connection to the outside environment. Light penetrates a few millimetres and traces of moisture are held within the rock matrix. The algae are revealed only when thin flakes of rock are removed. At high altitude sites such as Linnaeus Terrace (1650 m), southern Victoria Land, the turnover time for cryptoendolithic biomass has been estimated to be about 10,000 years. Coastal communities tend to be dominated by the green alga *Desmococcus olivaceus* and *Prasiococcus calcarius* although also common are the blue-greens *Leptolyngbya* sp. and *Chroococcidiopsis* sp. At Linnaeus Terrace, lichen-dominated communities are most common but others are dominated by algae. The green unicellular *Hemichloris antarctica* occurs below overhanging rocks at intensities less than 0.01% of incident light. This is one of very few Antarctic endemic algae. Unicellular, colonial blue-green *Gloeocapsa* spp. grow in close proximity to the lichen-dominated community while *Chroococcidiopsis* sp. is rarely found in especially cold and dry habitats.

Snow algae occupy a very different habitat of ice crystals irrigated by meltwater. Microenvironmental temperatures do not, or barely, exceed 0°C. A small range of psychrophilic algae are able to grow vigorously enough to tint the snow a pinkish-red, green, yellow, or grey. Snow algae are most prominent in coastal regions of maritime Antarctica and the fringing lower latitudes of continental Antarctica. Their furthest south is at Ross Island (76°43′ S). They are absent from the vast majority of snow surfaces in Antarctica. Although most often sighted in the vicinity of nesting birds, snow distant from such nutrient sources can also contain visible populations. For instance, extensive grey snow at Windmill Islands is

Examples from Selected Literature of Numbers of Species of Algae from Different Taxonomic Groups Found in Contrasting Habitats and at Contrasting Localities

Location	Lat./Long.	Habitats Studied*	Species Numbers										Reference
			Total	CY	CH	HET			DI	CR	EU	RH	
						BA	XA	CHR					
Sub-Antarctica													
Îles Kerguelen and Îles Crozet	49°00′ S 69°00′ E and 46°00′ S 51°00′ E	A	294	77	192	ND	9	4	2	0	9	1	Thérézien & Couté 1977
Macquarie Island	54°25′ S 158°58′ E	A, NA	52	ND	ND	52	ND	ND	ND	ND	ND	ND	Bunt 1954
Maritime Antarctica													
Signy Island, South Orkney Islands	60°43′ S 45°38′ W	NA	165	49	66	28	20	1	1	0	0	0	Broady 1979
South Orkney and South Shetland Islands	60°43′ S 45°38′ W and c. 62°00′ S 60°00′ W	A	234	ND	ND	234	ND	ND	ND	ND	ND	ND	Håkansson & Jones 1994
King George Island, South Shetland Islands	62°00′ S 58°30′ W	A, NA	68	68	ND	ND	ND	ND	ND	ND	ND	ND	Komárek 1999
Continental Antarctica													
Vestfold Hills	68°35′ S 78°00′ E	NA	83	34	36	8	5	0	0	0	0	0	Broady 1986
Schirmacher Oasis	70°40′ S 11°30′ E	A, NA	217	100	56	56	2	2	1	0	0	0	Pankow, Haendel, & Richter 1991
Southern Victoria Land	77°00′ S 162°52′ E	A, NA	97	33	28	27	3	5	0	1	0	0	Seaburg et al. 1979
La Gorce Mountains	86°30′ S 147°00′ W	A, NA	18	6	11	1	0	0	0	0	0	0	Broady & Weinstein 1998

*Habitats: A, aquatic; NA, nonaquatic. †Algal divisions and classes: CY, Cyanobacteria; CH, Chlorophyta; HET, Heterokontophyta; BA, Bacillariophyceae; XA, Xanthophyceae; CHR, Chrysophyceae; DI, Dinophyta; CR, Cryptophyta; EU, Euglenophyta; RH, Rhodophyta. ND, not determined.

coloured by unicellular green algae *Chloromonas rubroleosa* and *Mesotaenium berggrennii*. Communities are usually dominated by species that are able to accumulate pigments, such as red carotenoids, which act as screens from high intensities of insolation, including ultraviolet radiation.

PAUL BROADY

See also **Aerobiology; Algal Mats; Cryoconite Communities; Cryptoendolithic Communities; Desiccation Tolerance; Dry Valleys, Biology of; Exobiology; Food Web, Freshwater; Heated Ground; Introduced Species; Lichens; Oases, Biology of; Phytoplankton; Snow Chemistry; Soils; Streams and Lakes; Vegetation**

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ALGAL MATS

Algal mats are perhaps the most widespread microbial communities in Antarctica. They consist basically of a mesh of microscopic algal filaments embedded in their own mucilaginous sheaths, which in turn trap and bind sediment particles, providing shelter as well as nutrients to other algae, bacteria, heterotrophic microorganisms (flagellates, rhizopods, ciliates), and even metazoan (rotifers, tardigrades, and nematodes). Because of this structural complexity they are also referred to as *microbial mats*.

Many scientists use the term *cyanobacterial mats* on account of the almost invariably dominance of filamentous cyanobacteria ("blue-green algae"), most of which belong to the order Oscillatoriales (genera *Phormidium, Oscillatoria,* and *Leptolyngbya* among others). Commonly, nitrogen-fixing genera such as *Nostoc, Anabaena,* and *Nodularia* are also frequent. Diatoms, mainly represented by *Navicula muticopsis* and *Pinnularia borealis* can surpass cyanobacteria in species richness, but not in biomass. Green algae do not contribute substantially to algal mats except for a few nitrophilous species and the green mats dominated by macroscopic *Prasiola crispa.* Growth and development of algal mats also involves seasonal changes in species composition.

Algal mats thrive in a wide range of environments, from wet soils or constantly flushed ones, to the bottom of temporary pools and ephemeral runnels, to the channels of permanent rivers, to the edges and bottom of cryoconite holes and deep, permanently frozen lakes. In response to this wide spectrum of ecological conditions, they vary in thickness (from less than 4 mm to more than 3 cm), species composition, and colour. Differently coloured mats in one same area can represent distinct species compositions.

Well-lit algal mats from soils and shallow water bodies have a layered structure, with reddish upper layers formed by dead filaments or by a dense mesh of actively moving Oscillatoriales. These layers are rich in mucilage, sheath pigments, and carotenoids that provide the whole community with protection against desiccation and high irradiances. Lower layers are typically dark green and host a higher number of species, which includes cyanobacteria as well as diatoms and few green algae. They have high chlorophyll-*a* concentrations and generally display a higher photosynthetic activity. Algal mats from the dimly lit bottom of lakes have a photosynthetically active upper layer and an anoxic, heterotrophic low layer.

Resistance to desiccation and to high irradiance facilitates the colonization of suitable environments by algal mats. Often, the same species composition can be found in algal mats of lakes and the surrounding terrestrial areas, and between those mats covering the bottom of deep lakes and small cryoconite holes in the same area.

Daily mat production can be as high as 1 to 38 mg $C.m^{-2}.day^{-1}$, widely surpassing that of phytoplankton in the same lake. Moreover, algal mats can cover extensive areas of flushed soils at sites in continental Antarctica. On account of this, they are the main source of carbon fixation in a vast region of Antarctica. Therefore, algal mats can be regarded as very successful communities playing a key role in Antarctic ecosystems, and deserve close attention within the context of a changing environment.

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See also **Algae; Biodiversity, Terrestrial; Colonization; Dessication Tolerance; Nematodes; Rotifers; Soils; Streams and Lakes; Tardigrades**

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AMSTERDAM ALBATROSS

The Amsterdam albatross *(Diomedea [exulans] amsterdamensis),* a member of the great albatrosses family Diomedeidae, is the rarest albatross of the Southern Hemisphere, breeding exclusively on Amsterdam Island (southern Indian Ocean, 37°50′ S, 77°32′ E). These birds were first mentioned in 1951, some 255 years after the island's discovery. The birds were described as a new species in 1983, but the taxonomy remains controversial. For example, some researchers suggest that Amsterdam albatrosses are a subspecies of the Wandering albatross *(D. exulans).*

Nevertheless, the great albatrosses evolved from a pelagic seabird species that originated in the Northern Tethys Sea approximately 54–38 Ma. These albatrosses then colonized the Southern Ocean, where several populations became isolated during the Pleistocene glaciations.

Adults (4.8–8 kg, males slightly larger than females) have an overall dark brown body and tail, with a lighter belly and white face and throat. Wings are brown on the dorsal side and white on the ventral side with black tips and trailing edges. The light pink bill has a black cutting edge to the upper mandible and a dusky tip. Plumage characteristics lighten with age, but juveniles and adults can be confused with certain populations of *D. exulans* (e.g., those from New Zealand).

Amsterdam albatrosses feed exclusively at sea upon fish and squids but their exact diet is unknown. During incubation, adults travel 200–1400 km per day (maximum distance of 2200 km from colony) making loops in a mostly northeast direction.

Males arrive on the Plateau des Tourbières (the only breeding ground, a peat bog of ~170 ha) in late January and build a conic nest using vegetal materials. When females arrive, partners exhibit spectacular displays including rare flight displays with vocalizations. Pairs bond for life. A single egg is laid in late February and both parents alternate incubation shifts (~7.5 days) before hatching occurs after 79 days, and brooding shifts (~2.5 days) until the chick becomes thermally independent (~28 days). The chick is then left alone and fed by both parents for another 7 months. Chicks depart alone in January–February and remain at sea for 4–8 years before returning to breed.

Breeding is biennial unless breeding failure occurs early. This strategy is associated with long life expectancy (at least 30–40 years), delayed first reproduction (7–10 years), high breeding success (71%–73%), and high adult survival (~96%).

Only 5–10 pairs bred each year in the 1980s and 15–20 during the late 1990s. The total population in 2005 totaled 120 to 150 birds. Prior breeding range and demographic simulations suggest that the population decreased before 1980, with the probable cause being mortality at sea resulting from bycatch in longlining fisheries. Breeding habitat was also threatened by introduced cattle until the French administration initiated efforts to protect it. Over the past 20 years, the population has increased by about 70%, suggesting that it may still be viable. However, recent discovery of avian cholera in the sympatric yellow-nosed albatross *(Thallassarche chlororynchos carteri)* represents a serious threat, as infection is already suspected. Amsterdam albatrosses are considered critically endangered by IUCN, with a high risk of extinction, based on their low population size and being a single-island endemic species.

Yann Tremblay

See also **Albatross and Petrels, Agreement for the Conservation of; Albatrosses: Overview; Amsterdam Island (Île Amsterdam); Introduced Species; Wandering Albatross**

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AMSTERDAM ISLAND (ÎLE AMSTERDAM)

Amsterdam Island, in the southern Indian Ocean (37°50′ S, 77°32′ E), is one of the most isolated islands in the world. It is roughly oval in shape and covers 55 km^2. It is entirely volcanic in origin and numerous cones have been created during the last century. Steep cliffs (30–60 m) skirt most of the coastline, those at the west being up to 700 m high. The eastern part of the island slopes gently up from the sea to the central plateau (an old caldera) where it rises to 881 m (Mont de la Dives). Another small volcanic island, St. Paul Island (38°43′ S, 77°30′ E), 8 km^2 in area, lies 89 km to the south.

The location of Amsterdam Island, north of the subtropical convergence, strongly influences its climate: Mean annual air temperature is 13.8°C (11.2°C in August, 17.0°C in February), and annual rainfall is about 1127 mm per year, according to Météo-France records for 1951–1996. This oceanic and mild climate at the sea level changes in higher altitudes where the conditions are similar to those observed in the sub-Antarctic islands. There is no river or lake, only small ponds in the mires on the high plateau. The lowland remains very dry, especially during summer, and several fires occurred in the past.

Lowland slopes to 250 m are dominated by meadows of tussock grass *Poa novarae*. Dense grasslands of sedges *Scirpus nodosus* and *Spartina arundinacea* occur to about 600 m. At higher altitude, vegetation comprises feldmark of dwarf shrub *(Acaena magellanica),* sphagnum bogs, and mosses. Near the coast, the vegetation has been deeply modified by cattle *(Bos taurus),* introduced on the island in 1871. Introduced plant species have been favoured by grazing, and the formerly widespread tree *Phylica nitida,* up to 7 m high, and ferns, were recently restricted to few sheltered areas.

Moseley's rockhopper penguin *(Eudyptes chrysocome moseleyi),* yellow-nosed albatross (*Diomedea chlororhynchos bassi,* 37,000 pairs, 80% of the world population), sooty albatross *(Phoebetria fusca),* and the rare endemic Amsterdam albatross (*Diomedea amsterdamensis,* less than fifty breeding pairs) are the main breeding bird species. Amsterdam Island fur seal *(Arctocephalus tropicalis)* breed on the island (population of about 35,000 adults), and southern elephant seal *(Mirounga leonina)* occurs as nonbreeder. Introduced mammals are widespread: cattle, Norwegian rats, mice, and cats.

In 1988, a management plan was developed to reduce the effect of grazing on soil erosion, plant disturbance, and threats to birds, namely to the Amsterdam albatross. Fences have been erected and cattle from the southern part of the island were removed. In addition, more than 7,000 *Phylica nitida* have been planted. Whereas restoration processes are slow in the most eroded areas, vegetation close to the original one, without alien species, is now established at the south of the island.

Amsterdam Island was discovered by Sebastian del Cano (on one of Magellan's ships) in 1522, but was not landed on until 1696 by Van Vlaming. It was claimed by France in July 1843. The permanent scientific and meteorological station Martin de Viviès has been continuously operated by the Terres Australes et Antarctiques Françaises since 1951. It hosts about twenty people in winter and forty in summer. The crayfish industry operates around Amsterdam and St. Paul Islands.

Yves Frenot

See also **Amsterdam Albatross; Flowering Plants; France: Antarctic Program; France: Institut Polaire Français Paul-Emile Victor (IPEV) and Terres Australes et Antartiques Françaises (TAAF); Introduced Species; St. Paul Island (Île St. Paul); Sooty Albatross; Southern Elephant Seal; Yellow-Nosed Albatross**

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AMUNDSEN, ROALD

Roald Engelbregt Gravning Amundsen was born in Hvidsten, southeast Norway, July 16, 1872, and he died June 18, 1928, when his plane disappeared into the sea off Bjørnøya, Svalbard. He made his career and his name within polar exploration and logistics, and he is assessed today as one of the most successful of polar travellers.

Amundsen stated that he decided to become a polar explorer when reading Sir John Franklin's books at the age of 15. At 17 he was in the crowd that turned out to honour Fridtjof Nansen on his return from the first crossing of Greenland, and this experience sharpened his resolve. His mother wanted him to become a doctor, and it was only after her death in 1893 that he could devote his time to his own choice of career.

In addition to the hard physical training in which he had already engaged, including skiing and swimming, he worked on an Arctic sealer in 1894. Expeditions to the Arctic or Antarctic at that time usually included a voyage by ship, and Amundsen read enough reports to understand that there could be problems when the expedition leader had to relate to a ship's captain. He therefore took his first mate's and captain's certificates in order to secure full control of his future expeditions.

In the summer of 1896, he was chosen as an unpaid able seaman and ski expert for the Belgian Antarctic Expedition on the *Belgica*. Appropriate participants were not easy to find, and Amundsen was promoted to second mate before departure. During the expedition he gained his first significant experience in the polar regions, with expedition doctor Frederick Cook as his mentor. They tested various types of equipment, such as sleeping bags, tents, and sledges, and they proved the effect of seals and penguins as a protection and cure for scurvy. Amundsen learned about survival techniques and leadership, and took his first ski trip on the Antarctic continent.

Amundsen was no scientist; he sought geographical conquests. However, he understood that sponsors and the public wanted scientific façades for expeditions, and he therefore equipped his own first expedition to determine the current position of the North Magnetic Pole. However, the real goal was the first complete navigation of the Northwest Passage, which was accomplished 1903–1906 on the *Gjøa*. During the expedition's almost two-year stay on King William Island, Amundsen learned from the Inuit many details with regard to successful polar travel, including dogsled driving, clothing, food, and igloo-building techniques.

The North Pole was Amundsen's next great polar goal, and he declared his second expedition to be a repeat and extension of Nansen's drift over the Arctic Basin in the *Fram*. News that both Frederick Cook and Robert E. Peary claimed to have reached the North Pole took away Amundsen's inducement to go north, and his attention turned to another great goal—the South Pole. He kept his change of plans secret until the last moment, thereby committing himself, his reputation, and his future career to getting there first. He believed that failure in any way, including arriving second to Robert Falcon Scott, would leave him as a cad who had unsuccessfully tried to perform a dirty trick. Accusations and hurt feelings, on the other hand, would drown under the acclamation of a tremendous feat.

Amundsen's 1910–1912 Antarctic expedition was a model of polar logistics and planning. He and four companions reached the South Pole on December 14, 1911, a month before Scott, and returned to his base camp at the Bay of Whales with scarcely any problems to report.

On the personal side Amundsen was less successful. He needed to be the absolute leader, and could not tolerate real or imagined criticism from his men. When Nansen's companion from the Arctic, Hjalmar Johansen, challenged his leadership, Amundsen removed Johansen from the Pole group and assured that he arrived back in Norway in disgrace. During the *Belgica* expedition's forced wintering in Antarctica, Amundsen had removed himself from the expedition over a slight he felt he had received from the leader. However, he informed expedition leader Adrein de Gerlache that he would stay with the group until they reached civilisation again!

World War I represented a time change in many ways, not least concerning transport methods, and Amundsen was quick to see that aircraft could revolutionise polar exploration. He bought one of the first planes to reach Norway, and he took the country's first civil pilot's licence, in September 1915. The plane, however, was quickly donated to the military. Amundsen's expedition on the *Maud,* 1918–1925, was to be the North Pole expedition to which he had previously committed himself. It was successful in obtaining important scientific results, but Amundsen left it in 1922 when it became obvious that ships were no longer the right transport method for his ambitions. He had on the way completed a navigation of the Northeast Passage, the third in history, thus making him the first to circumnavigate the Arctic.

Amundsen's last expeditions were all with aircraft in the Arctic. In 1923, on the Alaskan coast, his plane was damaged before a planned flight over the Arctic Ocean was realised. In 1925, he flew with Lincoln Ellsworth, Hjalmar Riiser-Larsen, and three others from Svalbard to 87°43′ N in two aircraft, *N24* and *N25*. The following year the Amundsen-Ellsworth-Nobile Transpolar Flight in the dirigible *Norge* flew over the North Pole while travelling from Svalbard to Alaska. Amundsen thus became the first person to have been at both Poles.

Amundsen was now 55 years old, unmarried, with constant financial problems and with a bitter tendency to fall out with his nearest associates. He had been almost unsurpassed as a polar explorer and expedition leader with the traditional methods of skis and dogsleds, but the modern means of transport made him more of a passenger than a dynamic leader. When Umberto Nobile crashed on the ice with his dirigible *Italia* in 1928, Amundsen rose to the occasion and set out to look for him in a French aircraft with five others. They disappeared into the Arctic, and only two pieces of the plane were ever found.

Amundsen was decorated by many countries for his feats as a polar explorer, and numerous book and films have been produced about his life.

Susan Barr

See also **Belgian Antarctic *(Belgica)* Expedition (1897–1899); British Antarctic *(Terra Nova)* Expedition**

(1910–1913); British Antarctic *(Terra Nova)* Expedition, Northern Party; Dogs and Sledging; Ellsworth, Lincoln; Hanssen, Helmer; Norwegian *(Fram)* Expedition (1910–1912); Ponies and Mules; Riiser-Larsen, Hjalmar; Scott, Robert Falcon; Wisting, Oscar

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AMUNDSEN-SCOTT STATION

Amundsen-Scott Station is the year-round United States research facility at the geographic South Pole. The station has been operated and occupied continuously since 1956.

When a US Navy ski-equipped R4D airplane landed at the site on October 31, 1956, to begin construction, it brought the only humans to have reached the surface there since Norwegian and UK parties led by Roald Amundsen and Robert F. Scott first attained the Pole in 1911 and 1912. (Richard E. Byrd of the United States flew over the South Pole, but did not land, on November 29, 1929.)

The 1956 arrival—a flight from McMurdo Station, on the Antarctic coast—marked the start of building a research station for the 1957–1958 International Geophysical Year. The first winter of occupation, 1957, nine support personnel and nine scientists conducted meteorology, seismology, glaciology, and ionospheric and auroral studies.

The IGY station, most of it beneath the surface of the snow, was operated until 1975, when new structures sheltered under a geodesic dome on the surface replaced it. The dome facility was designed to last about 25 years. Construction of yet a third central station facility—this one on stilts to prevent buildup of drifted snow—began in the 1990s with completion scheduled for 2007.

The 2005 winter population was 86, and the 2004–2005 summer season population peaked at more than 220. Some of these occupants were building the new station, which, when completed, is intended to accommodate 50 in winter and 150 in summer. As at other US facilities in Antarctica, most residents were Americans with grants for research or employed by US contractors for science support or construction. But a substantial number were scientists from other Antarctic Treaty nations working with US counterparts on cooperative research projects.

The Antarctic Plateau is a uniquely valuable location for astrophysics, climatology, glaciology, seismology, and other sciences. The extremely cold and dry atmosphere is transparent and dark throughout the infrared and millimeter wavelengths, making the South Pole one of the world's best places for telescope observing in those spectra. The station's location at the Earth's axis of rotation enables continuous observation of celestial bodies for weeks at a time, unaffected by the 24-hour rise-and-set interruptions of lower latitudes.

The air at the South Pole is some of the cleanest air on Earth, and yet daily sampling of it since 1957 has recorded, in trace amounts, the gradual global buildup of chlorinated fluorocarbons, lead from leaded gasoline, and other anthropogenic chemicals. This monitoring has helped scientists build the baseline against which to understand atmospheric trends in temperate latitudes nearer the sources of these substances.

The ice sheet itself is used as a detector of neutrinos. Originating in some of the farthest reaches of space and thus recording some of the earliest moments of the universe, these high-energy particles nearly always pass through substances unimpeded and unnoticed. On rare occasion, however, neutrinos interact with water or ice molecules. Scientists have buried photomultiplier tubes deep in the ice beneath the station to detect these interactions. An initial group of detectors proved the concept in the 1990s; starting in 2000, an additional array of detecting tubes was being designed and installed to instrument an entire cubic kilometer of ice with 4,800 photomultipliers. The project, called IceCube, was the largest research project at the South Pole and projected to cost nearly $300 million over its first 13 years of construction and operation. The project was expected to open unexplored bands of the electromagnetic spectrum for astronomy.

Other new facilities for astronomy and astrophysics include a 10-meter telescope being built in the 2000s to investigate properties of the dark energy that pervades the universe and accelerates its expansion, to constrain the mass of the neutrino, to search for the signature of primordial gravitational waves, and to test models of the origin of the universe.

Other research at Amundsen-Scott has included seismology to detect and characterize earthquakes worldwide, climate monitoring, ozone-hole studies, glaciology including ice core drilling for study of past climates, detection of microscopic life in the ice, and medical and psychological study of the human response to the cold, the high altitude, the long absence of sunlight in winter, and the annual 8½-month isolation in a remote yet confined environment.

To optimize the science, Amundsen-Scott South Pole Station and its surroundings are divided into sectors, each having an environment best for specific activities. The operations sector houses the main station and general operations. The clean air sector is upwind of the station for sampling pristine air and snow for climate research. The quiet sector limits noise and use of equipment to enable seismology and other vibration-sensitive pursuits. The radio frequency sector is reserved for communications equipment. The downwind sector, free from obstructions, is for balloon launches and aircraft operations. The dark sector is for astrophysics and is free of light pollution and electromagnetic noise.

The station is on the central Antarctic Plateau at an elevation of 2935 meters, which happens to be about the same thickness as the snow, firn, and ice on which it rests, making the nearest land almost 2 miles away—straight down. The ice is moving in the general direction of South America at about 10 meters a year; an annual ceremony is the setting of a new marker on the snow surface showing the exact location of the geographic South Pole—90°00′00″ S latitude. The extreme cold suppresses the atmospheric pressure, sometimes making the elevation seem like as much as 4000 meters. The ice plateau is featureless except for sastrugi to the horizon. Winter low temperature has reached –82.8°C, and the record high in summer was –13.6°C. Unlike Antarctica's coasts, the station does not get strong breezes; the wind averages 5.5 meters per second and has never exceeded 24 meters per second.

The South Pole is supplied entirely from the coastal station McMurdo during the 100 or so days of summer when outdoor operations are practical. Ever since the South Pole station was opened in 1956, airlift has been the sole method of transporting people and supplies over the 838 miles of ice and mountains. In the early 2000s, oversnow traverse equipment was being tested to carry cargo and fuel and perhaps relieve some of the demand on airlift.

GUY G. GUTHRIDGE

See also **Amundsen, Roald; Antarctic Ice Sheet: Definitions and Description; British Antarctic *(Terra Nova)* Expedition (1910–1913); Climate Change; East Antarctic Shield; Firm Compaction; Geospace, Observing from Antarctica; International Geophysical Year; Ionosphere; McMurdo Station; Meteorological Observing; Norwegian *(Fram)* Expedition (1910–1912); Pollution Level Detection from Antarctic Snow and Ice; Scott, Robert Falcon; South Pole; United States: Antarctic Program**

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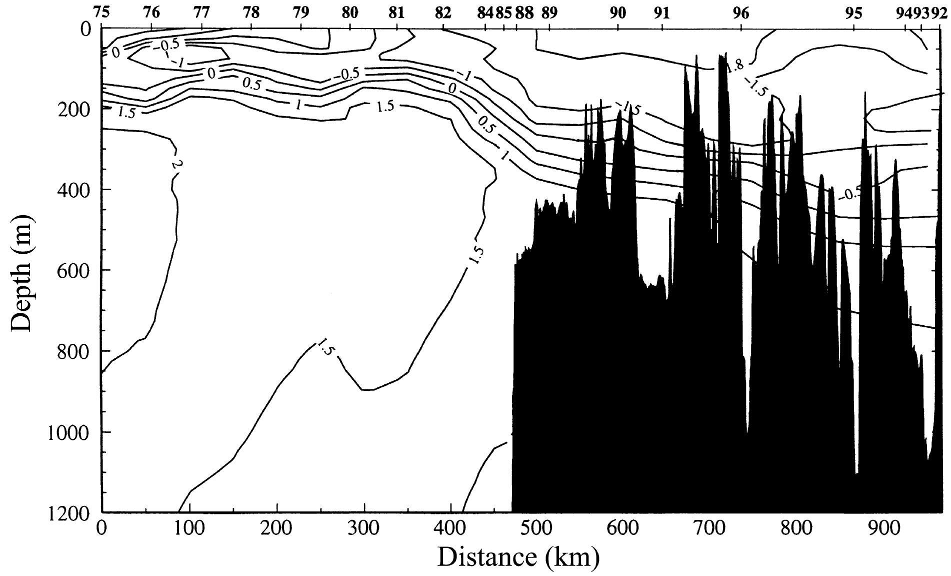
AMUNDSEN SEA, OCEANOGRAPHY OF

The Amundsen Sea lies off the coast of Marie Byrd Land between Cape Dart on Siple Island (126°09′ W) and Cape Flying Fish on Thurston Island (102°29′ W). Its northern limit is undefined, and in some studies its western boundary is extended toward the Ross Sea at Cape Colbeck (157°54′ W). Named for Roald Amundsen, who almost reached it while drifting westward on the *Belgica* in March 1899, the region was first visited by the *Resolution,* on which Captain Cook achieved his highest southern latitude, at 71°10′ S, 106°54′ W. On January 30, 1774, he wrote: "The outer or Northern edge of this immense ice field was composed of loose or broken ice so closely packed together that nothing could enter it; about a Mile in began the firm ice, in one compact solid body, and seemed to increase in height as you traced it to the South; In this field we counted Ninety Seven Ice Hills or Mountains, many of them vastly large.... We could not proceed one inch farther South...." The Amundsen Sea has since been visited by US expeditions in 1839, 1939–1941, 1946–1947, 1961, and several times during the 1985–2000 period, and by Norwegian, German, and British expeditions in 1929, 1994, and 2003.

Nearly perennial sea ice, often held fast by numerous grounded icebergs, continues to complicate travel and research in the Amundsen Sea. The extent and concentration of the sea ice cover has been monitored by satellites since the early 1970s, and the state of its ice shelves since the 1990s. Its sea-floor characteristics and ocean and sea-ice properties are slowly being revealed by work from research icebreakers that began in the 1990s. Biological observations indicate patchy areas of high productivity at all trophic levels. Regional applications of a circumpolar ocean model,



A vertical temperature section in the eastern Amundsen Sea extending from ~66.5° S (left) to ~74.5° S (right) between 101.3° W and 103.5° W. South of ocean station 89, this traverse encountered the rugged bottom topography of the eastern and southern continental shelf in Pine Island Bay. The waters warmer than 0°C that blanket the deep floor of the shelf here are common throughout the Southeast Pacific sector, unlike the colder waters that characterize shelf regions from the Ross westward through the Weddell Sea. (Modified from a figure by Hellmer et al. in Antarctic Research Series Vol 75, 1998.)

driven by realistic atmospheric forcing, are broadly consistent with ocean measurements. Refinements await more accurate bathymetry, more *in situ* meteorological data, and higher model resolution.

The Amundsen Sea continental shelf broadens westward, from approximately 200 km around Thurston Island and under the Abbot Ice Shelf to more than 500 km along 104° W past the King and Canisteo peninsulas and under the Pine Island Glacier. It then narrows to approximately 200 km near 120° W around Carney Island and to close to 100 km near 135° W, beyond the western end of the Getz Ice Shelf. Minimal bottom relief occurs at its 400–700 m deep outer limits, but broad sills deepen southward into very rough troughs, some exceeding 1500 m depths near ice shelf calving fronts. These troughs were cut by grounded glaciers during past ice ages and contain a variety of geomorphological features ranging from subtle lineations to hundred-meter scale topography. Large islands appear to anchor the northern edges of the lengthy Abbot and Getz ice shelves, while numerous small islands populate areas on the southeastern shelf and near Siple Island, often masquerading as icebergs, or vice versa. Bathymetry is unknown under the ice shelves, which currently occupy up to 25% of the continental shelf area.

Studies of the sea-ice cover using satellite data have typically grouped the Amundsen and Bellingshausen seas, covering the sector from 60° to 130° W. The sea ice displays a later summer minimum than in the Ross or Weddell seas, and a negative trend in ice extent over the three-decade record. Fast ice is more common than are polynyas, which tend to be small and intermittent during winter near the coastline. Satellite feature tracking and modeling of ice drift indicates that a large percentage of the sea ice formed in the southern Amundsen is exported to the Ross Sea, while a large fraction of the sea ice found in the northern Amundsen has been imported from the Ross. Sea-ice drifters set near the continental shelf break in the eastern Amundsen have tracked generally westward over the outer shelf, slope, and rise for periods of 8–16 months. A giant iceberg from the Thwaites Glacier Tongue followed a similar westward path after being grounded for decades on the shelf, then drifted north and east via the Antarctic Circumpolar Current through the Drake Passage.

Ocean properties on the Amundsen Sea continental shelf are transitional between those on the slightly warmer Bellingshausen and the markedly colder and saltier Ross continental shelves. Relatively warm and salty Circumpolar Deep Water intrudes near the sea floor, and is particularly noticeable in Pine Island Bay on the eastern shelf. More than 3°C above the *in situ* melting point, this inflow fuels melting deep beneath the regional ice shelves and glacier tongues, resulting in the upwelling of meltwater along the coastline. In some locations glacier basal melt rates appear to be two orders of magnitude higher than beneath the largest Antarctic ice shelves, and such rapid melting may account for local ice shelf thinning and faster offshore flow of grounded ice. It also influences the local sea-ice cover and could contribute to observed freshening downstream in the Ross Sea. Melting is inferred from measurements of ocean temperature, salinity, helium, neon, dissolved oxygen, and oxygen isotopes and from considerations of glacial mass balance, while thinning is inferred from airborne and satellite altimetry.

The continental shelves of the Amundsen and Bellingshausen seas differ from the other large embayments around Antarctica by the general absence of cold, dense shelf waters. Shelf water production is damped by the southeasterlies that tend to move sea ice more along than away from the coastline, while brine production is limited by the thick ice and snow cover and countered by the melt-driven upwelling. Surface waters on the shelf are generally too light to be overturned to the sea floor, or to mix readily with deep water to form new bottom water. This situation evolves westward as a shelf break frontal region strengthens toward the Ross Sea where recently "ventilated" waters appear to descend along the continental slope.

Seaward of the continental slope and rise, the Ross Gyre extends to 130°–150° W, east of which the Antarctic Circumpolar Current expands southeast toward the continental shelf. That current then tracks eastward into the Bellingshausen Sea, moving faster than the westward drifts on the shelf to its south. The deep Amundsen Sea is thus similar to that in other sectors, dominated by the voluminous Circumpolar Deep Water sandwiched between the more seasonally variable Antarctic Surface Water and the Antarctic Bottom Water that has been generated elsewhere. Incursions of the Circumpolar Deep Water onto the adjacent continental shelf and its spatial and temporal variability in response to climate change are topics of current interest. The properties and circulation of this water, and its influence on ice shelf extent and thickness, could have implications for discharge from the West Antarctic Ice Sheet.

STANLEY S. JACOBS

See also **Antarctic Ice Sheet: Definitions and Description; Antarctic Surface Water; Bellingshausen Sea, Oceanography of; Circumpolar Current, Antarctic; Circumpolar Deep Water; Coastal Ocean Currents; Continental Shelves and Slopes; Ice Shelves; Icebergs; Polynyas and Leads in the Southern Ocean; Remote Sensing; Ross Sea, Oceanography of; Sea Ice, Weather, and Climate; Southern Ocean: Vertical Structure; Thwaites and Pine Island Glacier Basins**

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ANARE/AUSTRALIAN ANTARCTIC DIVISION

Exploration, exploitation, and science are inextricably linked, factors particularly true of Australia in Antarctica, which led to the establishment of the Australian National Antarctic Research Expeditions (ANARE) and the Australian Antarctic Division (AAD). In the early nineteenth century, Australia's proximity to the Southern Ocean, the sub-Antarctic islands, and Antarctica led ships to use the ports of Sydney and Hobart as a springboard for Antarctic exploration and in pursuit of whales and seals.

Throughout the 1800s, scientists in Australia, aided by the Royal Societies of the colonies, attempted to establish Antarctic committees to organize expeditions. Those that were organized, such as the proposed Swedish-Australian Antarctic Expedition, were doomed to failure due to lack of financial support, especially from governments. Henrick Bull and Carsten Borchgrevink, residents of Australia, were involved in the *Antarctic* expedition, and Louis Bernacchi, a Tasmanian physicist, accompanied Borchgrevink on his later *Southern Cross* expedition. The Australian government gave financial support to Robert Falcon Scott's 1901–1904 and Ernest

Shackleton's 1907–1909 expeditions, and a number of Australians accompanied these expeditions as well as Scott's 1910–1913 expedition.

Sir Douglas Mawson and Captain John King Davis gained valuable polar experience with Shackleton. They organized and led the Australasian Antarctic Expedition 1911–1914. This expedition of science and discovery was judged by its scale and achievements to be the greatest and most consummate of the era. Increasing national interests and whaling, especially by Norway, saw Mawson and Davis, supported by the British, Australian, and New Zealand governments, conduct two summer voyages in 1929–1930 and 1930–1931. The British, Australian, New Zealand Antarctic Research Expedition (BANZARE) traversed the coastline from 45° to 160° E, making landings and aircraft flights, and proclaiming lands to be British Territory.

A British Order-in-Council dated February 7, 1933, affirmed sovereign rights over the Antarctic territory and placed the region under control of the Commonwealth of Australia. The Australian Antarctic Territory Acceptance Bill 1933 received assent in June 1933 and came into operation three years later. During debate three reasons were given for the Act: territorial/strategic, economic potential, and long-range weather forecasting. As other nations' interests in Antarctica and whaling increased, it became obvious that effective occupation was necessary to preserve Australia's claims. Mawson put forward further proposals for scientific and exploratory expeditions, but these were all put on hold during World War II.

Cessation of hostilities in 1945 saw the resurgence of national interests in Antarctica, including whaling and Byrd's Operation Highjump. These, combined with Mawson's lobbying for an expedition, put further political pressure on the Australian government. On December 2, 1946, an interdepartmental committee was convened by the Department of External Affairs. It recommended to government that preliminary plans be drawn up for an expedition. The *Wyatt Earp,* Sir Hubert Wilkins' old vessel now owned by the Australian government, would be refitted and operated by the navy to find a suitable site for a base on the Antarctic Continent. On December 20, 1946, an announcement was made that a short reconnaissance voyage would be made to Antarctica.

The Executive Committee on Exploration and Exploitation was then formed. As it met, support for establishing meteorological stations at Macquarie Island and other islands in the South Indian Ocean came from the International Meteorological Organization. The Royal Australian Air Force (RAAF) commenced long-range reconnaissance flights over Macquarie Island and the Southern Ocean. In May 1947, Group Captain Stuart Campbell, who had been a pilot on BANZARE, was chosen as executive officer and leader of the expedition by an Executive Planning Committee which included Mawson and Davis, £150,000 was appropriated, and plans firmed for two island stations to be established with around twelve scientists and support personnel at each. Pressure for a Heard Island station came from Britain because of disputed territorial claims. Commander Carl Oom, another veteran of BANZARE, was selected to captain the *Wyatt Earp.* A second ship, a tank-landing LST 3501 *(HMAS Labuan),* was under the command of Lieutenant-Commander George Dixon.

July saw scientific equipment being purchased, and Phillip Law, a lecturer in physics at Melbourne University, chosen as senior scientific officer. He commenced to establish a science program. Shortly afterwards, the official title—Australian National Antarctic Research Expedition (ANARE)—was adopted; "expedition" became plural later. ANARE was attached administratively to the Department of External Affairs and represented all government agencies as well as the nongovernment organizations, including Australian universities and research institutions, foreign organizations, and commercial shipping and aviation firms. As well as having scientific and exploratory aims, it was to maintain Australian interests in Antarctica. Prime Minister Joseph Chifley announced the expedition on November 6, 1947.

The Heard Island expedition station was opened at Atlas Cove (53°05′ S, 73°30′ E) on December 26, 1947, and a station was opened on Macquarie Island (54°30′ S, 158°57′ E) on March 21, 1948 (this station still operates today). *Wyatt Earp* failed to reach the Antarctic continent because of the unsuitability of the ship, ice, and the lateness of the season.

In May 1948, the AAD was established as part of the Department of External Affairs and Stuart Campbell was made officer-in-charge and tasked with administering the Australian Antarctic Territory and the Territory of Heard and McDonald Islands (Macquarie Island is under the administration of Tasmania), providing logistic support for ANARE, and conducting research in a number of disciplines. Campbell returned to the Department of Civil Aviation in January 1949, and Phillip Law became officer-in-charge of the AAD. The position later became titled "director." Law presided over the fledgling organizations in an era of discovery and expansion of both stations and science.

The launching of the Danish ice-strengthened ship *Kista Dan* in 1952, chartered by the AAD in austral summer 1953–1954, facilitated the opening of the continental station in Mac.Robertson Land, Mawson

(67°36′ S 62°52′ E), on February 13, 1954. Mawson Station is named after Sir Douglas Mawson, a fitting tribute to his lifetime of Antarctic exploration and science and his advocacy of Australia's interests. The station is the oldest continuously operated one inside the Antarctic Circle. Heard Island Station was closed in March 1955, and has been reoccupied by a wintering group only once, in 1992; a number of summer expeditions have gone to the islands over the past 30 years.

Activity of the Soviets and the proposals from a number of nations to establish research stations in Antarctica for the International Geographical Year (IGY) 1957–1958 led to the opening of Davis Station (68°35′ S, 77°58′ E) in the Vestfold Hills on January 13, 1957. Davis was closed in January 1965 while a replacement station was being built for Wilkes. Davis reopened in January 1969, as did the new Casey Station (66°17′ S, 110°32′ E), near the US IGY Wilkes station, which had been placed under Australian custody in 1959. Casey Station continues to operate today although at a different site as a new Casey was opened in 1988. The naming of Casey after Lord Casey commemorated a public servant and politician who had done much for Australia's Antarctic interest in the 1920s and 1930s, was Minister of External Affairs when Mawson Station was established, and signed the Antarctic Treaty on behalf of Australia.

Major field traverses by dog sleds or tractors have included Wilkes to Vostok in 1962, Mawson to Southern Prince Charles Mountains and Enderby Land, Mawson to Amery Ice Shelf (where four men wintered in 1968), and Mawson to Davis around the Lambert Glacier basin in 1993–1994 and return to Mawson in 1994–1995. Numerous field camps were established in the Prince Charles Mountains, Enderby Land, Cape Denison, Scullin Monolith, and Gaussberg and on the Law Dome near Casey, a glaciological drilling site. In the 1980s, additional bases included Edgeworth David in the Bunger Hills, Law in the Larsemann Hills, and Dovers in the Northern Prince Charles Mountains. Since 1980–1981, an active marine science program has been supported during summer.

The initial ANARE scientific program expanded as universities collaborated with the AAD, which became the lead agency for Antarctic marine living resources, biology, glaciology, human impact, human biology and medicine, and cosmic ray physics. Other government agencies led atmospheric sciences, geosciences, and oceanography. Traditional disciplinary science has become multidisciplinary, with scientists from many organizations, including specific Antarctic cooperative research centers, all now focusing on priority areas of ice, ocean, atmosphere and climate, Southern Ocean ecosystems, and adaptation to environmental change. Science on ANARE was reduced in the 1960s and 1970s as old stations were rebuilt, Davis closed, and the Prince Charles Mountain surveys deferred.

From its inception, the AAD has advanced Australia's Antarctic interests with its significant research program. Equally important has been its presence in, and administration of, Australian Antarctic and sub-Antarctic territories. A director and four branch heads in Science, Operations, Policy Coordination, and Corporate, together with a staff of over 300, maintain four stations, manage and conduct the research, and provide logistics and transport. Having had a significant role in establishing the Antarctic Treaty, Australia through the AAD continues an important role in maintaining it, by supporting Australia's international obligations with respect to Antarctica. There is close liaison between the division and other government departments, state governments, universities, and international polar agencies, and bodies such as the Scientific Committee on Antarctic Research (SCAR) and the Council of Managers of National Antarctic Programs (COMNAP). The AAD's current vision is "Antarctica valued, protected and understood."

The stations from 1947 to 2004 have had over 200 station years and 3,000 persons wintering in over 4,000 positions; some personnel have spent up to ten winters in Antarctica. Women first traveled on ANARE in 1959, wintering for the first time at Macquarie Island in 1976 and on the continent in 1981. Summer populations are greater than winter populations. Changing scientific and building programs required the ice-strengthened ships *Nella Dan* and *Thala Dan* to be replaced in 1984 by a larger one, the *Icebird,* and the icebreaker *Aurora Australia* in 1989. This enabled more personnel to travel south. Aircraft have been used extensively by ANARE in Antarctica but not from Australia; RAAF flights of the 1950s were replaced by commercial companies and a wide range of aircraft in the 1960s and thereafter. Newer aircraft will commence in the 2004–2005 summer, flying between the stations and field locations. After a number of attempts over many years to provide an intercontinental service, trial flights between Hobart and Casey Station are scheduled to begin in the summer of 2006–2007 as a prelude to regularly scheduled flights the next summer.

In the 57 years of ANARE, the AAD has been part of a plethora of departments; initially with the Department of External Affairs, it has moved through the supply, science, and environment portfolios to its current parent, the Department of Environment and Heritage. As with most organizations totally dependent on government funding, the formulation of government policy depends to a large degree on the Minister and Secretary of the parent department and the director of the AAD, and their interaction; in the case of Antarctica, world politics such as the advent of the Antarctic Treaty has been another potent factor. Although a strong supporter of the Antarctic Treaty, Australia has still exerted the right to change its stance against the majority of Consultative Parties when personal and domestic views deemed it necessary. This was particularly true in the late 1980s with the adoption of the Convention on the Regulation of Antarctic Mineral Resources (CRAMRA) by the Antarctic Treaty Consultative Parties and subsequent reversal of policy by Australia as to signing, and the subsequent substitution with the Protocol on Environmental Protection to the Antarctic Treaty (the Madrid Protocol).

The complex interaction of persons, politics, and policy on the domestic front is illustrated by the 1981 move of the AAD from Melbourne to Kingston, a suburb of Hobart, 10 years after the move was announced. Stuart Campbell was executive officer of ANARE and officer-in-charge of AAD 1947–1949 with the following succeeding him: 1949–1966, Phillip Law; 1966–1970 and 1971–1972, Don Styles (acting); 1970–1971, Bryan Rofe; 1972–1979, Ray Garrod; 1979–1984, Clarrie McCue; 1984–1988, Jim Bleasel; 1988–1998, Rex Moncur; and 1998 to present, Tony Press. Each director influenced the AAD and ANARE in his own way.

Despite the evolution in science, technology, priorities, and personnel, the concept of ANARE—embracing the activities of government and nongovernment bodies and individuals, whether scientists or support, in Antarctica—and its relationship with the AAD are still relevant today. Attempts to remove ANARE from the vernacular have been unsuccessful thus far. As Australian science and exploration in Antarctica approaches 60 continuous years, the AAD and ANARE are on a much more permanent footing than the fledgling organization that struggled for its existence, after a gestation of over one hundred years.

DESMOND J. LUGG

See also **Antarctic: Definitions and Boundaries; Antarctic Treaty System; Australasian Antarctic Expedition (1911–1914); Australia: Antarctic Program; Aviation, History of; Borchgrevink, Carsten E.; British Antarctic *(Nimrod)* Expedition (1907–1909); British Antarctic *(Southern Cross)* Expedition (1898–1900); British Antarctic *(Terra Nova)* Expedition (1910–1913); British National Antarctic *(Discovery)* Expedition (1901–1904); British, Australian, New Zealand Antarctic Research Expedition (BANZARE) (1929–1931); Convention on the Regulation of Antarctic Mineral Resource Activities (CRAMRA); Council of Managers of National Antarctic Programs (COMNAP); Davis, John King; Heard Island and McDonald Islands; International Geophysical Year; Law, Phillip; Macquarie Island; Mawson, Douglas; Oases; Protocol on Environmental Protection to the Antarctic Treaty; Scientific Committee on Antarctic Research (SCAR); United States Navy Developments Projects (1946–1948); Whaling, History of; Wilkins, Hubert**

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ANDEEP PROGRAMME

ANDEEP (Antarctic benthic deep-sea biodiversity: colonisation history and recent community pattern) is a deep-sea expedition programme conducted from the research vessel *Polarstern* for the investigations of the biodiversity of the Southern Ocean deep-sea fauna. The aims of ANDEEP were to conduct the first base-line survey of the deep-water benthic faunas of the Scotia and Weddell seas, and to investigate the evolutionary and ecological processes and oceanographic changes in space and time that have resulted in the present biodiversity and distributional patterns in the Southern Ocean deep sea.

Unlike the fauna on the Antarctic shelf, which is very isolated and shows a high degree of endemism (*in situ* evolved species), the deep-sea fauna is not isolated. Although deepwater underlies most of the Southern Ocean and is extensive, it is still poorly known especially with respect to the composition and functioning of the Southern Ocean deep sea benthic communities.

It is possible that the Southern Ocean deep sea is a centre of evolution for benthic animals, as the shelf is believed to be. Most Antarctic benthic shelf species are likely to have reinvaded the shelves via the deep sea after glaciation, and Antarctic deep water fauna may have influenced the composition and species richness of the benthic faunas of the world oceans.

In 2002, the ANDEEP I (ANT XIX-2) and ANDEEP II (ANT XIX-3) expeditions from RV

Polarstern recovered a tremendous number of organisms of widely varying size from Drake's Passage, around the South Shetland Islands and Trench, the western Weddell Sea, and the South Sandwich Trough. During this survey it was possible for the first time to compare Southern Ocean deep-sea faunas to those collected elsewhere using standardised sampling strategies and similar apparatus. In March 2005, the ANDEEP III (ANT XXII-3) expedition sampled the deep sea along the Greenwich Meridian in the Cape Basin, Agulhas, and northern Weddell Sea Basins. A variety of sampling apparatus (CTD, a sediment profile imaging system, multiple corer, giant-box corer, epibenthic sledge, Agassiz trawl, and baited traps) were used during all three ANDEEP expeditions. A wide variety of organism taxa were collected from in and on the sea floor and much information on water and sediment quality was gained.

The ANDEEP expeditions revealed surprising results with regard to high benthic species diversity within all size classes. Within many groups of animals more than 80% of the species are new to science. ANDEEP contributes to the abyssal biodiversity data within CeDAMar, which is one of the core field projects of the CoML (Census of Marine Life), and aims at a documentation of actual species diversity of abyssal plains as a basis for global change and for a better understanding of historical causes and recent ecological factors regulating biodiversity.

Angelika Brandt

See also **Antarctic Bottom Water; Benthic Communities in the Southern Ocean; Biodiversity, Marine; Circumpolar Deep Water; Deep Sea; Marine Biology: History and Evolution; Scotia Sea, Bransfield Strait, and Drake Passage, Oceanography of; Weddell Sea, Oceanography of**

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ANHYDROBIOSIS

Although Antarctica has an enormous amount of freshwater, most of it is locked up as snow and ice or is otherwise unavailable to organisms. On the Antarctic continent organisms are largely restricted to areas of ice-free land (less than 0.5% of the continent is ice free) and to areas which receive sufficient meltwater in summer to support their growth. Sources of water, such as melting snowbanks, may become exhausted and the organisms have to tolerate desiccation. Anhydrobiosis (life without water) is the ability to survive a cessation of metabolism due to water loss.

Anhydrobiotic organisms survive the loss of more than 99% of their water and enter a state of suspended animation, in which their metabolism comes reversibly to a standstill. This ability is found in a variety of organisms, including nematodes, rotifers, tardigrades, some arthropods, some plants (mosses, resurrection plants, pollen, some seeds), bacteria (especially spores and cyanobacteria), fungi (spores, yeast), lichens, and protists (algae, protozoan cysts). These can survive for many years in a desiccated state. Although it has not been explicitly demonstrated in some groups, anhydrobiosis is probably widespread among terrestrial Antarctic bacteria (especially cyanobacteria), algae, mosses, fungi, protozoa, lichens, and terrestrial microinvertebrates (nematodes, rotifers, tardigrades). The mechanisms of anhydrobiosis have been best studied in nematodes, tardigrades, and cyanobacteria.

A slow rate of water loss is essential for anhydrobiosis. Antarctic nematodes and tardigrades living in soil or moss can rely on their environment losing water slowly, whereas those that inhabit more exposed sites (such as the aerial parts of lichens) may themselves control water loss from their bodies. A resistant cuticle with a restricted permeability helps control water loss, as does coiling (nematodes) and withdrawing the legs into the body (tardigrades), thus reducing the surface area exposed to the air. Cyanobacteria secrete a sheath of polysaccharides (large molecules consisting of repeating sugar units). These are hygroscopic (they absorb water) and thus slow down water loss during desiccation and aid water uptake during rehydration. A slow rate of water loss allows the orderly packing of internal structures and biochemical changes that help protect the organism from the effects of water loss. Most anhydrobiotic organisms produce the sugar trehalose and this is thought to protect membranes and proteins by replacing the water that forms part of their structure. There is increasing evidence that desiccation-induced proteins also play an important role in anhydrobiosis. During rehydration there is repair of any damage that occurred during desiccation and the physiological state of the organism is restored before movement and/or normal function commences.

The McMurdo Dry Valleys are the largest area of ice-free land in Antarctica. They are one of the driest places on Earth and evaporation in summer is so rapid that the permafrost (at 10–30 cm depth) cannot supply sufficient moisture to allow microbial growth to stabilise the surface. However, Dry Valley soils, in places, contain a community of organisms—including nematodes and tardigrades. The survival of organisms in this site, and in many other terrestrial Antarctic habitats, must be critically dependent upon anhydrobiosis.

David Wharton

See also **Biodiversity, Terrestrial; Desiccation Tolerance; Dry Valleys, Biology of; Nematodes; Tardigrades**

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ANTARCTIC ACCOUNTS AND BIBLIOGRAPHIC MATERIALS

Expedition materials range from letters and logbooks, through field notes, sledging books, and diaries to charts, maps, and scientific data in written, graphical, and digital forms. The earliest Antarctic expeditions were those of professional seamen such as James Cook and Fabian von Bellinghausen, who kept detailed logbooks on which the official published accounts could be based. Scientific data from these expeditions included not only direct measurements of physical phenomena, such as temperature and water depth, but also illustrations of the landscape and natural history prepared by draughtsmen. For the whaling and sealing expeditions of the eighteenth and nineteenth centuries, the only surviving records are normally logbooks, although these are extant for only a proportion of known voyages. The largest collection of such whaling logbooks is at the Old Dartmouth Historical Society Whaling Museum in New Bedford, Massachusetts.

The range of journals and other material produced by the expeditions of the "Heroic Age" is much greater. Many of the expeditions required the officers and scientists to maintain diaries that were to be made available to the expedition leader to help him write the official narrative. Often there was an embargo on these unofficial accounts being published immediately after the expedition in case they contradicted the leader or in any way undermined the impression he was at pains to create. However, during the past 100 years a range of contemporary accounts have been published for most major expeditions, often providing those human details missing from the official narrative. Robert Falcon Scott's expeditions have generated the greatest number of separate narratives, and even today some of the important contemporary narratives have yet to be translated from their original language.

The major expeditions produced their scientific findings principally as a range of specially written scientific reports. The most extensive scientific output from a single expedition is probably the eighty-five volumes produced by the First German Antarctic Expedition led by Erick von Drygalski, although the *Challenger* Expedition led by Wyville Thomson produced fifty volumes between 1885 and 1895. The continuing research on whales and the Southern Ocean conducted by the Discovery Investigations eventually led to the publication of thirty-seven volumes.

Special publications associated with overwintering had been produced in the Arctic in the nineteenth century. Recognising this, both Scott and Ernest Shackleton produced midwinter books (*South Polar Times* and *Aurora Australis*), a tradition continued by British Antarctic stations in the latter part of the twentieth century. In the twenty-first century, the continuing records collected in Antarctica are principally digital and, although accounts of visits there continue to be printed as books, online diaries and newspapers are becoming increasingly common.

With its limited history, lack of indigenous inhabitants, and predominantly scientific focus, Antarctica is the only continent for which a complete bibliography of all published scientific papers, books, and popular articles has been attempted. There were some early attempts to list the exploration literature, but these were only partial and generally reflected the country and language of the compiler. The most significant general ones of these were Chavanne et al. (1878), who attempted to encompass all the polar literature to that point; Denucé (1913), who compiled a bibliography for the International Polar Commission; and Breitfuss (1933), whose bibliography came out of his direct experience of working in the polar regions. A variety of specialised bibliographies on ice, whaling, ornithology, meteorology, biology, etc. were produced during the first half of the twentieth century, and there have been many others since.

The exploration literature per se has been followed by an incomplete listing of books, maps, and some papers (Spence 1980), and a beautifully illustrated and annotated list of the 150 most collectable books from Antarctic expeditions (Mackenzie 2001). The latter is remarkable for the illustration of each volume, often with extremely rare dust wrappers. The most recent bibliography of the "Heroic Age" is undoubtedly the best, having been fully researched through many libraries worldwide and providing professional definitive bibliographic details of each volume, including all its reprints and variants (Rosove 2001).

The scientists have been exceptionally well served for almost 60 years. An initial private card-based bibliography put together by John Roscoe (1951), photogrammatist on Operation Highjump and Operation Windmill, was finally published by part of US Naval Intelligence, but without any credit to Roscoe and without his being able to finish organising the entries and annotating them. It lists material in all original languages, organising half of the content under science and most of the rest under individual expeditions. It proved a milestone and an important lever in getting the Department of Defense to begin funding both the *Antarctic Bibliography* and the CCREL Bibliography through a contract to the Library of Congress.

The *Antarctic Bibliography,* which began in 1965, originally provided monthly listings accumulated into annual volumes. Back listing eventually took the bibliography back to 1951, thus incorporating much of the literature of the International Geophysical Year. The efforts of the compilers in Washington ensured that coverage of English and Russian language material was very good, but it proved difficult to collect the growing diversity of material in other languages. Much of this, especially in European languages, has been captured in the catalogue of the Scott Polar Research Institute (SPRI), published by G. K. Hall in 1976 and now available online at www.spri.cam.ac.uk/resources/sprilib/antarctica/.

The last *Antarctic Bibliography* volume was issued in 1995 and was superseded by a subscription-based CD system. The entire bibliography is now available online at http://www.coldregions.org/antinfo.htm.

Antarctic manuscript and journal material is spread throughout the world, in both public collections and privately owned. The largest public depositaries are probably at SPRI, the National Maritime Museum in Greenwich, and the US National Archives, but there are also important collections in the Royal Geographical Society, the Mitchell Library (State Library of New South Wales, Sydney), the Alexander Turnbull Library (Wellington), the Arctic & Antarctic Institute (St. Petersburg,) and the Mawson Centre (South Australian Museum, Adelaide).

David W. H. Walton

See also **Bellingshausen, Fabian von; Books, Antarctic; British Antarctic *(Terra Nova)* Expedition (1910–1913); British National Antarctic *(Discovery)* Expedition (1901–1904); *Challenger* Expedition (1872–1876); Cook, James; Discovery Investigations (1925–1951); German South Polar *(Gauss)* Expedition (1901–1903); International Geophysical Year; Scott Polar Research Institute**

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ANTARCTIC AND SOUTHERN OCEAN COALITION (ASOC)

The Antarctic and Southern Ocean Coalition (ASOC), formed in 1978, is a global coalition of environmental nongovernmental organizations (NGOs). ASOC aims to achieve permanent protection for Antarctica's wilderness and wildlife through the creation of a "World Park Antarctica" (or a comparable regime), the maintenance of the demilitarised status of the area, and the continuation of international cooperation. ASOC promotes strategic approaches to addressing current and emerging issues facing the Antarctic region and its governance regime—particularly commercial pressures—with a view to long-term ecological sustainability. It also promotes continued openness of the Antarctic Treaty System (ATS) to NGO participation in environmental policy debates.

The interest of public advocacy organizations in Antarctic affairs predates the 1959 Antarctic Treaty, with increased NGO involvement starting in the mid-1970s in the United States, the United Kingdom, and elsewhere. As the exploitation of Antarctic marine living resources intensified, and the exploitation of mineral resources became a distinct possibility, some individuals and NGOs—notably James N. Barnes, a lawyer from the Center for Law and Social Policy, a US public interest NGO—sought to develop a worldwide coalition of environmental organizations to protect Antarctica (Kimball 1988; Suter 1991).

ASOC has been active at key Antarctic meetings since 1978. Its participation was at first limited to lobbying outside the meetings and to NGO representation on some national delegations (initially the United States, subsequently several other parties). The initiation of the negotiations for the Convention on the Regulation of Antarctic Mineral Resource Activities (CRAMRA) in 1982 resulted in a global environmental campaign opposing mining in Antarctica and promoting the development of an Antarctic conservation regime both in land and at sea. ASOC played a key role in this campaign (Elliott 1994; Darby 1994; Firth 2005), jointly with Greenpeace, which went on to develop its own on-the-ground Antarctic program. The NGO campaign combined direct action in Antarctica with analysis (Wallace 1988), political work domestically in most Antarctic Treaty states, and lobbying in Antarctic fora and at the United Nations. In the process ASOC gained participating "Expert" status to the meetings of the 1980 Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) in 1988 and to the formerly secretive Antarctic Treaty Consultative Meetings in 1991. ASOC remains the only environmental NGO with such status in the ATS. Since the early 1980s, ASOC also has attended, as observer, the meetings of the International Whaling Commission.

NGO efforts catalysed the rejection of CRAMRA by Antarctic Treaty states in 1989. The minerals convention was never ratified, and a 50-year open-ended prohibition on mineral resource activities became a key element of the 1991 Protocol on Environmental Protection to the Antarctic Treaty that was negotiated instead. Subsequently ASOC campaigned both domestically and internationally for the protocol's ratification until it entered into force in 1998. Since then ASOC has campaigned to promote the legal and practical implementation of the protocol (Bastmeijer 2003); to stop illegal, unregulated, and unreported fishing activities in the CCAMLR area; and to advance regulation by Antarctic Treaty states of the rapidly growing Antarctic tourism industry and of the fledging bio-prospecting industry.

ASOC is a loose coalition but it has maintained the active support of its key members over the years. ASOC membership includes some of the largest international environmental organizations worldwide, several dozen prominent national and issue-specific NGOs, and individual supporters. ASOC supports its activities with membership dues, foundation grants, and donations. ASOC Secretariats were established at various times in different countries, with the Antarctica Project in Washington, DC being the longest serving.

ASOC's involvement in Antarctic affairs has been variously resented, berated, and commended by governments and industries active in the region. Over the years ASOC has submitted many alternative proposals on Antarctic environmental management and policy issues. A number of these proposals have been rejected, but others have taken root. Several key elements of the Antarctic Treaty System as it is today—such as the prohibition on mining, the environmental protection protocol, the ecosystem management approach of the Southern Ocean fisheries regime, the Antarctic Treaty Secretariat, the Committee for Environmental Protection, the protocol's 2005 liability annex, and the ongoing discussion on the regulation of commercial tourism—resonate with proposals developed or supported by ASOC, and with its long-term goal of a World Park Antarctica.

RICARDO ROURA

See also **Antarctic Treaty System; Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Convention on the Regulation of Antarctic Mineral Resource Activities (CRAMRA); Greenpeace; International Whaling Commission (IWC); Protocol on Environmental Protection to the Antarctic Treaty; Tourism**

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ANTARCTIC BOTTOM WATER

The world ocean is cold, with an average temperature of 3.5°C. Warm waters are mainly found in a relatively thin surface layer at temperate and low latitudes. Even at the equator, where the surface temperature may be some 26°C–28°C, the temperature decreases steadily downwards, reaching near freezing temperatures (0°C) at some 4000–5000 m depth. Since the very first deep-sea measurements, it has become obvious that the bottom waters obtained their characteristics at high latitudes, and further research has shown that the Antarctic is of paramount importance in supplying cold water to the deep world ocean.

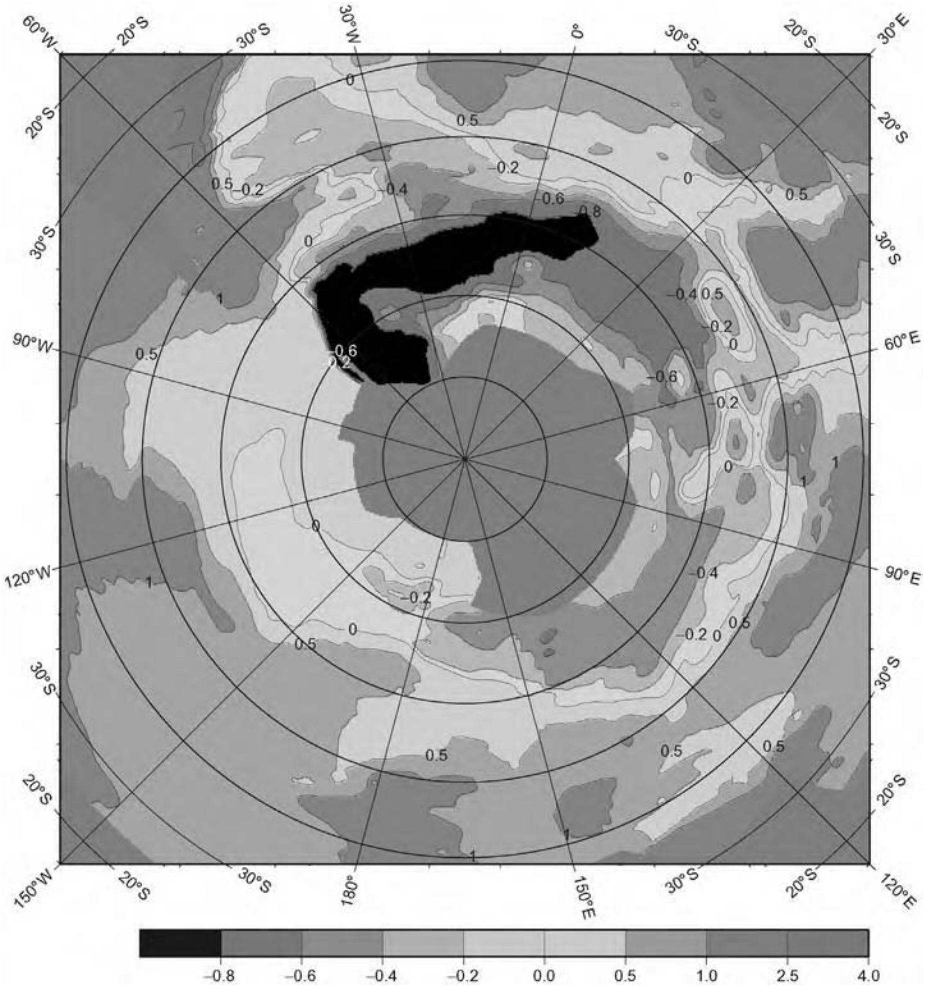
The lowest temperatures in the Southern Ocean appear in the southwest part of the Weddell Sea, and the temperature increases monotonically to the east and north. The data also show a strong correlation between low temperatures and high oxygen values. The impression given is that there is a source of cold, oxygen-rich water in the southern Weddell Sea. This cold, oxygenated water spreading out from the Weddell Sea (and from other sources along the Antarctic continent) is termed Antarctic Bottom Water (AABW). It has been estimated that about 60%–70% of the new AABW flows out of the Weddell Sea. Besides the Southern Ocean, the AABW occupies the deep North Pacific and South Pacific, the Indian Ocean, and the Atlantic Ocean. In the Atlantic, the AABW can be traced north to Bermuda where it meets cold water from the Arctic. Waters of Antarctic origin occupy the major part of the deep world ocean. Knowledge of the processes leading to the formation of AABW is therefore extremely important for an understanding of the climate of the world ocean. The supply of oxygen that is needed by marine life makes AABW equally important for an understanding of the health of the world ocean.

The Floating Ice Shelves

The Antarctic continent is covered with the world's largest ice cap, which contains more than 70% of the world's fresh water. Part of this ice sheet is floating on the sea, and nearly half of the continent is surrounded by floating ice shelves, which provide a large and active interface with the surrounding ocean. The cold water must be formed somewhere on the broad and relatively shallow shelves in the southern Weddell Sea. It can be seen that a major contribution to the formation of AABW is intimately coupled to processes under the floating ice shelves in the Weddell Sea. Several physical processes there are active in the production of the dense water mass that is obviously needed to form bottom water.

Typically, the distance from the ice front of the Filchner-Ronne Ice Shelf (FRIS), in the southern Weddell Sea, to the grounding line is about 500 km; the thickness of the FRIS at the ice front is about 300–500 m; and the depth at the grounding line perhaps 1500 m. The ice shelves constitute the drainage areas for the central ice sheet, and the glacial ice melting near the grounding line may originate from snow falling at a height of 3000–4000 m in the interior.

On the continental shelf during winter, sea water is subject to strong surface heat loss, and the water column is cooled by subsequent mixing and convection. When the freezing point is eventually reached, further cooling induces freezing of ice at the surface. However, when sea water freezes, most of the salt is rejected from the ice. It mixes into the underlying water, which then becomes saltier and denser. The cold and dense water mass thus formed is named high-salinity shelf water (HSSW). The amount of ice being frozen on the shelf near the FRIS is much higher than farther out on the open sea. This is due to offshore winds that carry the newly frozen ice away from the ice front, leaving open water or thin ice exposed to the cooling stress. Also, the tides produce periodic leads near the ice front, and freezing there becomes intense. The total ice production near the ice

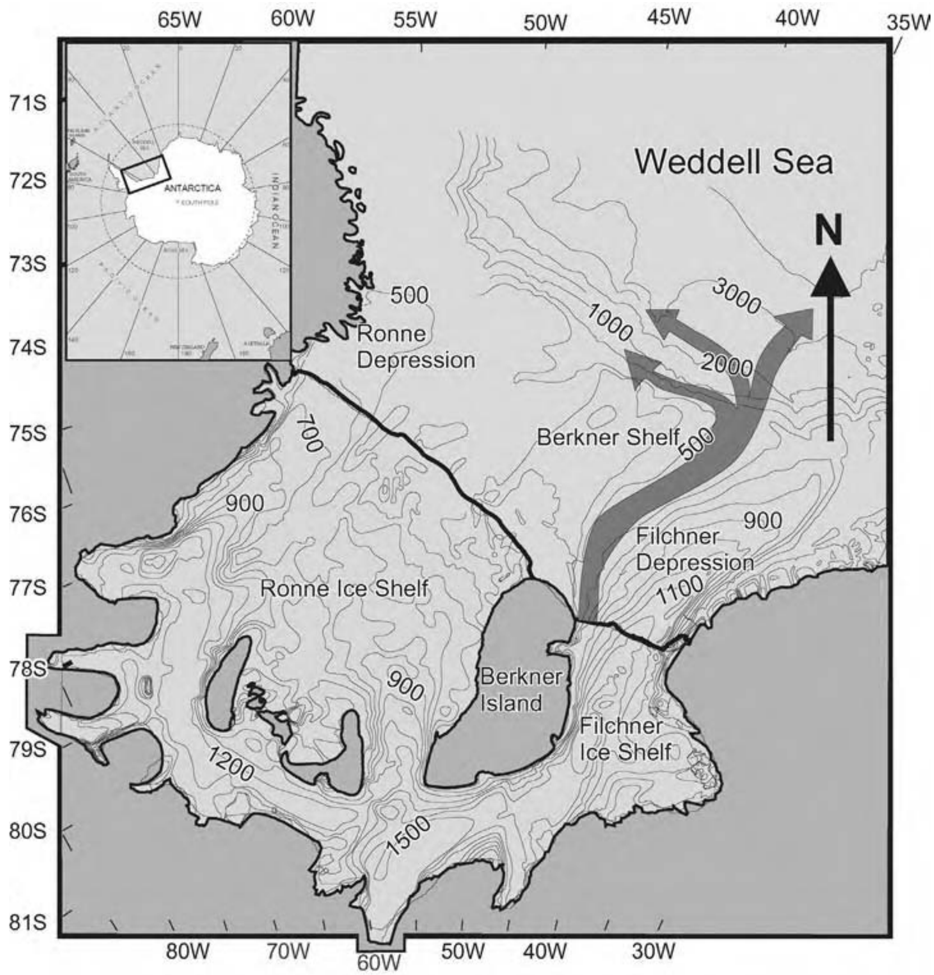


The potential temperature (in °C) near the bottom of the Southern Ocean. Note that the temperature in the deep ocean increases from a minimum in the southern and western Weddell Sea, showing that the source of cold water is located in that region. (Data source: http://woceatlas.tamu.edu)

front may contribute 20–30 times the ice production of the open ocean. This ice factory is the real key to the water mass transformation producing HSSW on the shallow shelf.

The unique thermal ice–ocean boundary of the FRIS plays an essential role in the formation of AABW. The shelf water circulates under the FRIS, and the importance of this ice–water contact is seen by studying the thermodynamics of sea water. The freezing point of sea water decreases with depth at a rate of 0.75°C km^{-1}. For ordinary sea water the freezing point at the surface is about –1.9°C, whereas at 500 m and 1000 m depth it is close to –2.3°C and –2.7°C, respectively. Thus, shelf water outside the FRIS at its freezing point is as cold as it can possibly be due to cooling at the surface. However, when this water moves under the FRIS it appears as a relatively warm water mass that is capable of melting glacial ice at the ice–ocean boundary, since its temperature is higher than the *in situ* freezing point. The meltwater adds to the water column, which becomes colder and slightly less saline in the process. Water having temperatures below the freezing point at the sea surface is termed ice shelf water (ISW). In nature, ISW can form only under floating ice shelves or large icebergs.

The addition of glacial meltwater gives ISW exceptional properties. The glacial ice melting near the grounding line may originate from snow falling over the ice sheet at some 3000 m height or more. For this snow the ratio of the oxygen isotopes O18/O16 is much less than at sea level because the heavier isotope O18 has fractionated out at lower levels. The same holds for other isotopes like helium. The glacial meltwater thus provides the ISW with isotope anomalies that are used as a tool (together with temperature, salinity, etc.) in tracing water masses.

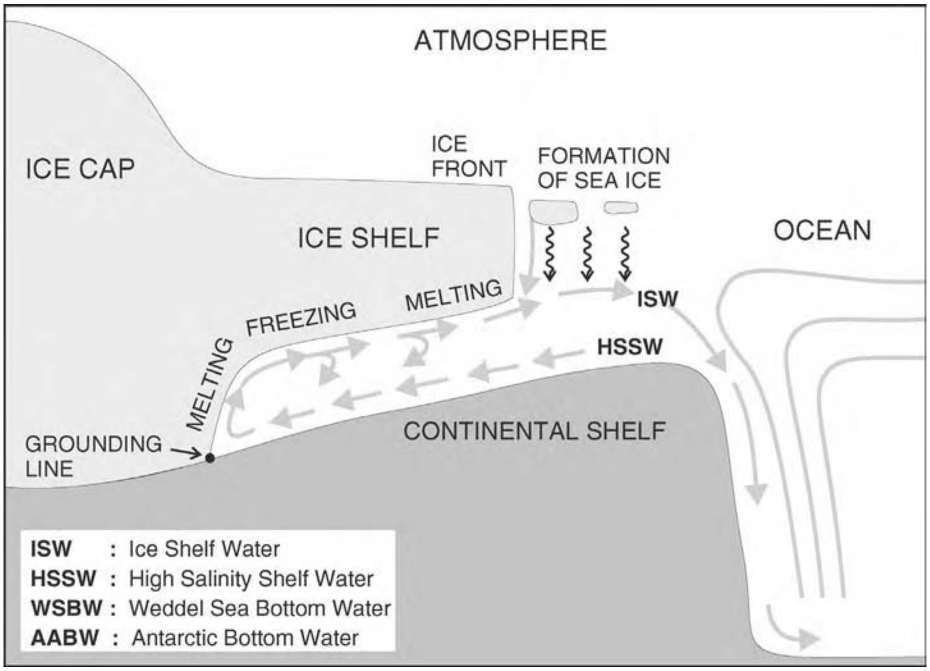


The local topography in the southern Weddell Sea with the floating Filchner and Ronne ice shelves. Depths are in meters. The flow of ISW originating under the FRIS and leaving the shelf break north of the Filchner Depression is shown by the three-pronged arrow. (See also Foldvik et al. 2004.)

The Formation of Bottom Water

The Norwegian Antarctic Research Expedition 1976–1977, in *Polarsirkel,* located a major source of ISW overflowing the sill (~600 m depth) of the Filchner Depression. Field investigations have shown that this ISW water attains its characteristics in several successive steps. First, cooling and surface ice freezing on the Berkner Ice Shelf produce HSSW. Second, the dense HSSW then flows south under the FRIS and around Berkner Island, becoming ISW by the melting of glacial ice and subsequent cooling. The salinity of the ISW becomes less than that of the HSSW, but it is still distinctly higher than that of the shelf water from which HSSW was derived. With its low temperature, ISW becomes sufficiently dense to descend the continental slope. Many years of current meter records of the ISW flowing out of the Filchner Depression area have shown that the annual mean temperature of the flow is –2.0°C and that the average volume flow of ISW is 1.6 Sv ± 30%, where 1 Sv = 10^6 cubic meters per second (21 cubic miles per day). This is considerably more than the total transport of all rivers on the planet Earth together.

This enormous river of extremely cold water rushes down the continental slope at high speed. The overflow may take different paths at the shelf break depending on the actual oceanographic conditions at the time of the overflow. Most of the mixing with the overlying warm deep water (WDW) takes place below 2000 m. The result is newly formed Weddell Sea Bottom Water (WSBW), which then flows west and north and into the deeper parts of the Weddell Sea. The apparent source of cold water is WSBW. The production of WSBW (referenced to –0.8°C) corresponding to the above release of ISW is 4.3 Sv ± 30%.



The circulation of ice shelf water, high-salinity shelf water, Weddell Sea bottom water, and Antarctic Bottom water.

On its way north, the newly formed WSBW mixes with the overlying Deep Water to form AABW. Recent estimates of the rates of production of AABW are about 10–15 Sv.

Sources of Antarctic Bottom Water

A major contribution to the formation of AABW in the southern Weddell Sea is believed to arise from the FRIS area as described previously. However, the ice shelves farther west in the Weddell Sea also produce cold and dense water. The Ross Ice Shelf undoubtedly produces cold and dense water contributing to the formation of bottom waters, but apparently much less than the Weddell Sea. Numerous ice shelves around the Antarctic continent border the sea and modify the adjacent waters. Their quantitative effect on the production of bottom water is not clear.

Bottom water may also be formed by open ocean convection. The best known example is the Weddell Sea Polynya, an enormous area of open water appearing during winter within a region normally covered by sea ice. Open water exposed to very low temperature produces large upward heat fluxes, cooling the water mass and breaking down the stratification. Cold and dense surface waters may then sink and contribute to the renewal of bottom water. The Weddell Polynya was observed during the mid-1970s and has not reappeared. The overall importance of this process for the formation rate of AABW is therefore probably small.

At the continental slope outside the shelf break resides a relatively warm saltwater mass known as the warm deep water (WDW). As long as the HSSW is lighter than the WDW, it will not be capable of moving under the WDW down the slope. However, during winter the density of HSSW increases and may equal the WDW density. Mixing of HSSW and WDW, in any proportion, will then produce a mixture that is denser than any of the two parent water masses and thus able to move down the slope. This shelf-break mixing is known as cabbeling and is due to the nonlinearity of the equation of state for sea water. The extent to which this process contributes to formation of bottom water is not known.

Biological Consequences

The shelf processes of cooling and convection provide efficient contact between the sea water and the atmosphere. This facilitates the uptake of oxygen and other atmospheric gases that are most efficient at low temperatures. The melting of glacial ice at high pressure and low temperature increases the oxygen content even further. These cold and oxygenated waters are advected into the bottom layers of all major ocean basins and are slowly being displaced upwards due to new supplies of bottom water. Since biological processes consume oxygen, the oxygen content of the water diminishes with time and also diminishes from the bottom upwards. There are regions (such as the northeast Pacific) where the oxygen levels are low due to long residence time, but all major ocean basins are oxic within the present climate situation.

Climate change could conceivably change the present situation. The production of HSSW is sensitive to a reduction of cooling stresses (wind strength and temperature). A reduced production of HSSW would reduce the production of ISW and hence the production of AABW. The melting rates under the FRIS might also be altered with consequences for the stability of the ice sheet.

ARNE FOLDVIK

See also **Circumpolar Deep Water; Continental Shelves and Slopes; Ice Shelves; Polynyas and Leads in the Southern Ocean; Southern Ocean: Fronts and Frontal Zones; Thermohaline and Wind-Driven Circulations in the Southern Ocean; Weddell Sea, Oceanography of**

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ANTARCTIC: DEFINITIONS AND BOUNDARIES

Antarctica is the continent that lies over the geographical South Pole, the southern end of the Earth's axis of rotation. The floating ice shelves that are seaward extensions of the continental ice sheet form an integral part of the "land" surface of the continent. It is normally considered to include the islands immediately adjacent to the continent, many of which are located within ice shelves or are attached to the continent by ice shelves. Along the western side of the Antarctic Peninsula the off-lying islands such as the Biscoe Islands, the islands of the Palmer Archipelago, and the South Shetland Islands are also regarded as part of the continent.

The Antarctic region has variously defined boundaries for various purposes. The northern limit of jurisdiction for the Antarctic Treaty is the 60° parallel of South latitude, a convenient political boundary that does not relate to any physical feature. The northern limit of jurisdiction for the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) is more complicated because it attempts to follow closely the Polar Front by defining latitudinal boundaries.

The Polar Front (previously known as the Antarctic Convergence) is an oceanographical feature where the cold, dense Antarctic surface waters of the Southern Ocean sink beneath the warmer surface waters of the southern Atlantic, Indian, and Pacific oceans. This is also a climatic boundary and is frequently marked by fog. It is also an ecosystem boundary for many marine species, which is the reason it was chosen by CCAMLR for the extent of its jurisdiction. It is also the boundary adopted by the Scientific Committee on Antarctic Research (SCAR) because it is defined by natural features, including the northern limit of the Antarctic Circumpolar Current.

The Polar Front is widely accepted as the natural northern limit of the Antarctic region but, for juridical and some other purposes, it is more convenient and practical to define a more arbitrary northern limit.

The following islands and island groups lie south of the Polar Front but do not form part of the Antarctic continent: Bouvetøya, Heard Island, MacDonald Islands, Balleny Islands, Scott Island, Peter I Øy, South Georgia, South Orkney Islands, and the South Sandwich Islands.

The Antarctic Circle lies at 66°33′ S and marks the latitude above which the Sun does not rise on Midwinter Day (21 June) and does not set on Midsummer Day (21 December). Moving south of the Antarctic Circle the number of days without the Sun in winter and with 24-hour sunlight in the summer gradually increases. At the South Pole, the Sun rises on 22 September, the vernal equinox, and does not set again until 23 March, the autumnal equinox.

In addition to the geographical South Pole, three other poles are recognized in the Antarctic: the South Magnetic Pole, the South Geomagnetic Pole, and the Pole of Inaccessibility.

The map of Antarctica in a polar stereographic projection showing the whole continent (as opposed to a Mercator projection where the continent is depicted as a wavy border of white at the bottom of the map) can immediately be seen to comprise two parts. Greater Antarctica is the larger part that lies between the Transantarctic Mountains and the coast bordering the Southern Ocean south of the southern Indian Ocean and the southwestern Pacific Ocean. Lesser Antarctica is the smaller part that lies between the Transantarctic Mountains and the coast bordering the southeastern Pacific Ocean and the southern Atlantic Ocean. The Transantarctic Mountains themselves form part of Greater Antarctica.

Commonly used synonyms for Greater Antarctica are East Antarctica and Eastern Antarctica and those for Lesser Antarctica are West Antarctica and Western Antarctica. The justification for West and Western Antarctica is that it lies entirely within the Western Hemisphere but the converse for East and Eastern Antarctica is less precise as it lies largely within the Eastern Hemisphere but partly in the Western Hemisphere. These names also give rise to the seeming paradox that on the Ross Ice Shelf, East Antarctica lies to the west and West Antarctica lies to the east. The terms Greater and Lesser Antarctica have been largely supplanted in the literature by East and West Antarctica, which is a pity as they are neither accurate nor immediately obvious.

Lesser Antarctica comprises the major regions of the Antarctic Peninsula, Ellsworth Land, and Marie Byrd Land, together with the Ross Ice Shelf and the Filchner-Ronne Ice Shelf.

The Antarctic Peninsula (55°–80° W) extends northward from Ellsworth Land for about 1500 km and may be considered to include the off-lying islands of the South Shetland Islands across Bransfield Strait. The section of the peninsula north of a line from Cape Jeremy to Cape Agassiz is known as Graham Land, and that south of the line as Palmer Land. Historically, the northeasternmost part of the peninsula was known as the Trinity Peninsula.

The Antarctic Peninsula is dominated by a high central plateau, very narrow in places, that broadens gradually southward, and then broadens abruptly at the boundary between southern Graham Land and northern Palmer Land. Most of the exposed rock occurs in spectacular cliff faces buttressing the plateau, and on the inshore islands of the west coast. Steep glaciers and ice falls descend from the plateau between the cliffs. There are deep channels between the inshore islands, the best known being Lemaire Channel. Farther south, in Palmer Land and across George VI Sound on Alexander Island, the terrain is more mountainous. The east coast of the peninsula is

The Area of Antarctica

Area	Measurement
Antarctica, including islands and ice shelves	13,829,430 km^2
Antarctica, excluding islands and ice shelves	12,272,800 km^2
Ross Ice Shelf	510,680 km^2
Filchner-Ronne Ice Shelf	439,920 km^2
Ice-free area (0.32% of the continent)	44,890 km^2
Minimum extent of pack ice (March)	4,000,000 km^2
Maximum extent of pack ice (September)	22,000,000 km^2

Other Geographical Data

Feature	Measurement
Highest peak: Vinson Massif, Ellsworth Mountains	4892 m
Height of surface at South Pole	2771 m
Highest point of the ice sheet: Dome Argus	4093 m
Mean height of Antarctica, including ice shelves	1958 m
Mean height of Antarctica, excluding ice shelves	2194 m
Maximum known thickness of ice: Terre Adélie (69°54′ S, 135°12′ E)	4776 m
Mean thickness of ice	1829 m
Mean thickness of grounded ice	2034 m
Total volume of ice sheets, including ice shelves	25.4×10^6 km^3
Lowest temperature recorded: Vostok station	–89.6°C
Largest ice berg approximately 295 × 37 km (satellite image in 2000)	~11,000 km^2
Or possibly approximately 335 × 97 km (sighted from a ship in 1956)	~31,000 km^2

fringed by the Larsen Ice Shelf, the smaller northern parts of which (known as Larsen A and Larsen B) disintegrated in recent years. The peninsula region, particularly Graham Land, is rich with a variety of wildlife. Graham Land and the South Shetland Islands are relatively easy to reach by sea and hence witnessed some of the earliest exploration in the Antarctic. Similarly, in more modern times, many national stations and bases have been built in the region so that, as a result, more scientific research has been done in the region than elsewhere on the continent. More tourists visit this area than any other part of the Antarctic.

Ellsworth Land (80°–103° W) lies at the head of the Ronne Ice Shelf. It includes the Ellsworth Mountains and a number of small isolated groups of hills. The Vinson Massif, the highest mountain in Antarctica, lies in the southern part of the Sentinel Range that forms the northern part of the Ellsworth Mountains. There are several other high mountains in this range. Eights Station and Siple Station (United States) are the only scientific stations that have been built in this region and, as inland stations, they were supplied entirely by air. A commercial airline/tour company has operated from a summer camp at Patriot Hills for some years. The principal clients have been mountaineers climbing in the Ellsworth Mountains, adventurers proposing to walk to the South Pole, and other tourists who fly to the South Pole. It is in the sector of the Antarctic that is unclaimed. It was named after the American aviator Lincoln Ellsworth.

Marie Byrd Land (103°–152° W) is dominated by the western Antarctic Ice Sheet, punctuated by isolated young volcanoes, with outcrops of other rocks closer to the coast. A permanent fringe of sea ice has rendered the region largely inaccessible by ship, and only one coastal station, Russkaya (USSR), has ever been established. Access to the region has normally been by air or by overland tractor train. The United States Byrd Station was established by tractor train, and subsequently supplied by air, from McMurdo Station. A key feature of central Marie Byrd Land is the Bentley Subglacial Trough where the bedrock is deep below sea level. This is the reason that the western Antarctic Ice Sheet is considered to be inherently unstable and would collapse relatively quickly, given sufficient warming of the Antarctic climate. The sector was named for the wife of Richard E. Byrd, whose first expedition (1928–1930) did the initial exploration of the area.

Edward VII Land (152°–158° W) forms the eastern margin of the Ross Ice Shelf. There are some rock outcrops, notably the Rockefeller Mountains, in the immediate hinterland of its northern, seaward coast. To the south there is no outcrop, and the principal features are the five ice streams that flow westward from Marie Byrd Land into the Ross Ice Shelf. This sector was first discovered on the British National Antarctic Expedition (1901–1904) and named after the British monarch. It was initially reached from the Ross Ice Shelf by three members of Roald Amundsen's Norwegian Antarctic expedition (1910–1912).

Filchner-Ronne Ice Shelf (35°–75° W) is basically one ice shelf at the head of the Weddell Sea but it includes Berkner Island, which constitutes a major division between the two parts. Expeditions to the area have been relatively few because the Weddell Sea is permanently filled with ice and represents a largely impenetrable barrier to reaching the coast. Many ships have been ice-bound in the Weddell Sea and Sir Ernest Shackleton's *Endurance* was famously crushed and sunk in 1915. Wilhelm Filchner's German South Polar expedition (1911–1912) discovered the eastern section, and initially named it for Kaiser Wilhelm, but the German emperor asked that it be named for Filchner. The larger, western part was named for Edith Ronne, the wife of Finn Ronne, whose expedition in 1947–1948 discovered and photographed a segment of it. Perhaps the most important aspect of the ice shelf is that it is the source of the cold Antarctic Bottom Water that flows northwards along the abyssal plains into the world's major oceans.

The Ross Ice Shelf (160° E–160° W) is the largest in the world and is about the size of France. It was discovered on a British Antarctic expedition (1839–1843) under the command of James Clark Ross. It then was the Antarctic starting points for several of the expeditions of the "Heroic Era," notably those of Robert Falcon Scott, Ernest Shackleton, and Roald Amundsen in their attempts to reach the South Pole. Subsequently, during the 1920s and 1930s, the American Richard E. Byrd established the series of Little America stations in the area of the Bay of Whales. The glaciers of the Transantarctic Mountains and Marie Byrd Land feed enormous volumes of ice into the ice shelf, which has been the source of most of the largest icebergs recorded.

Greater Antarctica comprises the Transantarctic Mountains, the various named lands that extend eastward around the margin of the continent from the Weddell Sea to the Ross Sea and the major part of the Antarctic Ice Sheet, which covers the interior of the continent and is devoid of rock outcrop.

The Transantarctic Mountains extend from northern Victoria Land on the west side of the Ross Sea past the South Pole to the Horlick Mountains as an unbroken chain. Beyond the Horlick Mountains the outcrop is discontinuous but includes the Thiel Mountains and Pensacola Mountains. This is, perhaps, the obvious geographical extent of the

Transantarctic Mountains but it may be argued, on geological grounds, that they continue through the Shackleton Range and Theron Mountains in Coats Land to Heimefrontfjella and Vestfjella in Dronning Maud Land. The principal feature of the Transantarctic Mountains is that they form the boundary of Greater Antarctica within the continent and, in so doing, provide a dam to the flow of the Antarctic Ice Sheet that can escape seaward only through the many valley glaciers that flow into the Ross Sea and the Ross and Filchner ice shelves. Around 76°30′–78°30′ S lies the area known as the McMurdo Dry Valleys. These are glacially formed valleys in the mountains from which the glaciers have all but retreated. They have probably been ice-free for the past 4 million years. Despite having the coldest and driest climate on Earth, life still survives in the form of endolithic organisms.

Coats Land (37°–20° W) was discovered by William Speirs Bruce on the Scottish National Antarctic Expedition in 1904. The major rock outcrops are found in the Theron Mountains, Shackleton Range, and Whichaway Nunataks, where the initial survey and exploration was done by members of the Commonwealth Trans-Antarctic Expedition in 1957. There are small outcrops near the coast, where Littlewood Nunataks are the site of the Argentine General Belgrano II Station. The British Halley Station is located on the Brunt Ice Shelf. In common with most of the coast of Greater Antarctica, except northern Victoria Land, there is no rock outcrop and the edge of the continent is formed either by the front of ice shelves or by the ice sheet flowing directly into the sea.

Dronning Maud Land (20° W–45° E) is synonymous with the Norwegian territorial claim. The coast is fringed by ice shelves for most of its length but there are some outcrops along the Prince Olav Coast in the east. Inland there are several mountains ranges, all within 500 km of the coast, the spectacular faces and peaks of which provide new challenges to mountaineers and rock climbers. Some of the rocks in the regions are among the oldest in Antarctica, having formed more than 3000 Ma. In many areas there are extensive fields of hard blue ice that can be used by wheeled aircraft. One such area near the Schirmacher Hills forms the Antarctic end of an intercontinental flight from Cape Town, South Africa, using wheeled jet freighter aircraft for rapid deployment of equipment and personnel for the various national research programmes operating in the area. These programmes and stations include those of Belgium, Finland, Germany, India, Japan, Netherlands, Norway, Russia, South Africa, Sweden, and the United Kingdom. The area was first observed in January 1930 during flights by Hjalmar Riiser-Larsen during one of the series of Norwegian expeditions sponsored by Lars Christensen. It was named for the Queen of Norway.

Enderby Land (45°–55° E) was discovered in 1831 by John Biscoe while employed by the Enderby Brothers to seek further sealing grounds. There are groups of mountains close to the coast and farther into the hinterland, very similar in physiography to Dronning Maud Land. The Russian station of Molodezhnaya is located on the coast in western Enderby Land.

Kemp Land (55°–60° E) is a narrow sector that is almost devoid of rock outcrop. It was named for the British sealer Peter Kemp, who sighted the coast in 1833.

Mac.Robertson Land (60°–70° E) includes three major features: the Prince Charles Mountains, Lambert Glacier, and Amery Ice Shelf. The Prince Charles Mountains flank the western side of Lambert Glacier and the Amery Ice Shelf and the Mawson Escarpment lies on the eastern side. The Lambert Glacier is the largest glacier in the world. It is at least 400 km long and up to 64 km wide. It is the principal source of ice for the Amery Ice Shelf that forms the seaward extension of the glacier. The Pole of Inaccessibility for the continent and ice shelves (83°50′ S, 65°47′ E) lies in southern Mac.Robertson Land. The area, which is part of the Australian Antarctic Territory, was identified during the British Australian New Zealand Antarctic Research Expedition under Douglas Mawson, who named it in honour of the expedition's primary benefactor, Sir MacPherson Robertson, an Australian industrialist.

Princess Elizabeth Land (73°–86° E) has a predominantly ice coast but the coastal outcrops that do exist have provided sites for several stations, currently including the wintering stations of Zhong Shan (China) and Davis (Australia). In the past, the Soviet Union also occupied the wintering station Progress, close to the Zhong Shan. Inland are the Grove Mountains and Gale Escarpment. The ice sheet rises southward to Dome Argus (4095 m), the highest point of the ice sheet. Just north of Dome Argus lie the Gamburtsev Subglacial Mountains. This mountain range is entirely covered by ice and is known only from radio echo-sounding. A part of the Australian Antarctic Territory, it was identified during the British Australian New Zealand Antarctic Research Expedition under Douglas Mawson, who named it in honour of the young British Princess who became Queen Elizabeth II.

Wilhelm II Land (86°–91° E) was discovered on the German South Polar expedition (1901–1903) under Erich von Drygalski, who named it for the German Kaiser. It has virtually no exposed rock except for the prominent outcrop of Gaussberg, the core of an extinct volcano, which was named for the ship of the German expedition. The members of Douglas Mawson's Australasian Antarctic Expedition were the second to reach it, in 1912.

Queen Mary Land (91°–102° E) has an ice coast, including the Shackleton Ice Shelf. There is little exposed rock, but the Bunger Hills contain a number of seasonal lakes that are of great biological interest. The Russian station of Mirnyy is located on the coast and two former Soviet traverse stations, on the route from Mirnyy to Vostok Station, are located on the ice sheet to the south. The Shackleton Ice Shelf was first explored by the members of the Western Base on Douglas Mawson's Australasian Antarctic Expedition.

Wilkes Land (102°–136° E) has an ice coast for most of its length but the Australian Casey Station and the former United States/Australian Wilkes Station are both sited on rock. The Russian Vostok Station lies within Wilkes Land and, at 3448 m above sea level, is the highest manned station in the Antarctic. About 3800 m beneath the station is the upper surface of the southern end of Vostok Subglacial Lake, the largest of the known subglacial lakes. The joint French–Italian station Concordia is located on the summit of Dome Circe at 3233 m above sea level. The sector was named for Charles Wilkes, commander of the United States Exploring Expedition (1838–1842), which passed large portions of the area and spied "high land" at several places.

Terre Adélie (136°–142° E) is synonymous with the French territorial claim in Antarctica. The French station of Dumont d'Urville is located on Île des Pétrels in the Archipel de Pointe Géologie. Despite major protests and disruptive actions by Greenpeace, an air strip to accommodate intercontinental flights was completed close to the station by building causeways to join several islands. Subsequently a major storm destroyed part of the air strip and it has not been rebuilt. The South Magnetic Pole is currently located off the coast of Terre Adélie. The sector was named for the wife of Jules-Sebastien-Cesar Dumont d'Urville, the commander of the French naval expedition that discovered it in 1840.

George V Land (142°–155° E) has very little rock outcrop. Cape Denison was the site of the Australasian Antarctic Expedition (1911–1914) base under Sir Douglas Mawson, who named it for the British monarch. It is renowned for the strength and duration of the katabatic winds that can exceed 320 km per hour and is generally regarded as the windiest place in the world. Mawson originally considered Commonwealth Bay to be in "Adelie Land," and "King George Land" to apply to the newly discovered areas east of the Mertz Glacier, but when the French proclaimed sovereignty over Terre Adélie, "British Adelie Land" became part of what was King George Land.

Oates Land (155°–163° E) has little coastal outcrop but the western, inland flank of the Transantarctic Mountains forms much of its eastern margin. The former Soviet station Leningradskaya is located on the coast at 63°30′ S, 159°23′ E. The South Magnetic Pole was located in Oates Land in 1909 when it was approached by members of Ernest Shackleton's British Antarctic Expedition. Oates Land was named for Captain L. E. G. Oates of Robert Falcon Scott's last expedition, on which the coast was surveyed.

Victoria Land (163°–171° E) contains the Transantarctic Mountains from about 70°30′ to about 78°00′ S and includes Ross Island. This region was the scene of many of the early Antarctic expeditions from Sir James Clark Ross in 1840 to the Ross Sea party of Shackleton's Imperial Trans-Antarctic Expedition. Currently there are permanent stations on Ross Island (Scott Base, New Zealand; McMurdo Station, United States) and at Terra Nova Bay (Zucchelli Station, Italy). West of Ross Island in the Transantarctic Mountains is the Dry Valley region which has been largely ice-free for perhaps as long as 4 million years. Mount Erebus (3794 m) on Ross Island is the most active volcano in the Antarctic. The sector was named by Ross for Britain's young Queen Victoria.

PETER CLARKSON

See also **Adventurers, Modern; Aircraft Runways; Amundsen, Roald; Antarctic Bottom Water; Antarctic Circumpolar Current; Antarctic Ice Sheet: Definitions and Description; Antarctic Peninsula; Antarctic Treaty System; Australasian Antarctic Expedition (1911–1914); Balleny Islands; Bouvetøya; British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); British Antarctic *(Nimrod)* Expedition (1907–1909); British Antarctic *(Terra Nova)* Expedition (1910–1913); British, Australian, New Zealand Antarctic Research Expedition (BANZARE) (1929–1931); British National Antarctic *(Discovery)* Expedition (1901–1904); Bruce, William Speirs; Christensen Antarctic Expeditions (1927–1937); Christensen, Lars; Commonwealth Trans-Antarctic Expedition (1955–1958); Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Drygalski, Erich von; Dry Valleys; Dry Valleys, Biology of; Dumont d'Urville, Jules-Sébastien-César; Ellsworth, Lincoln; Filchner–Ronne Ice Shelf; Filchner, Wilhelm; French Naval (*Astrolabe* and *Zélée*) Expedition (1837–1840); German South Polar *(Deutschland)* Expedition (1911–1912); German South Polar *(Gauss)* Expedition (1901–1903); Heard Island and McDonald Islands; Imperial Trans-Antarctic Expedition (1914–1917); Lake Vostok; Larsen Ice Shelf; Mawson, Douglas; McMurdo Station;**

Mount Erebus; Norwegian *(Fram)* Expedition (1910–1912); Peter I Øy; Polar Front; Riiser-Larsen, Hjalmar; Ronne Antarctic Research Expedition (1947–1948); Ross Ice Shelf; Ross Sea Party, Imperial Trans-Antarctic Expedition (1914–1917); Scientific Committee on Antarctic Research (SCAR); Scott, Robert Falcon; Scottish National Antarctic Expedition (1902–1904); Shackleton, Ernest; South Georgia; South Orkney Islands; South Pole; South Sandwich Islands; South Shetland Islands; South Shetland Islands, Discovery of; Southern Ocean; Subglacial Lakes; Tourism; Transantarctic Mountains, Geology of; United States (Byrd) Antarctic Expedition (1928–1930); United States Exploring Expedition (1838–1842); Volcanoes; Vostok Station; Wilkes, Charles

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ANTARCTIC DIVERGENCE

The term *Antarctic Divergence* is applied, more often in the older literature, to a transitional zone between the eastward-flowing Antarctic Circumpolar Current and westward-flowing currents to the south. The former is driven by strong westerly winds and the latter by easterlies that result from cold, katabatic winds moving off the Antarctic continent. Owing to the Earth's rotation, the Coriolis force deflects the katabatic winds to the left, or the west, giving rise to the Antarctic Coastal Current.

Because surface water moves to the left of the wind in the Southern Hemisphere, Antarctic Surface Water diverges across this transition and upwelling is enhanced beneath. The upwelling may be evidenced by dome-shaped isotherms and isohalines below the sea surface, a salinity maximum near 200 m, or a minimum in surface water thickness. The vertical extent of the upwelling is quite large, as the warm and salty North Atlantic Deep Water rises from a depth of 2500–4000 m to reach the sea surface.

While the Divergence has little surface expression in shipboard or satellite observations, it can be a locus of lower sea ice concentration, fewer icebergs, and increased phytoplankton blooms resulting from the upwelled nutrients. It is not unusual, for example, for the Antarctic Divergence itself to be completely devoid of icebergs, while numerous ones are observed drifting in opposing directions just a few tens of miles away from, but on the opposite sides of, the Divergence. It is also associated with the centers of cyclonic gyres that occur over topographically distinct ocean basins between the Circumpolar and coastal currents. In the Atlantic, Indian, and most of the Pacific sectors, the Antarctic Divergence is found between 63° S and 66° S, but it is farther south in the southeast Pacific sector, reaching as far south as 70° S.

Igor Belkin

See also **Coastal Ocean Currents; Polar Front; Southern Ocean: Fronts and Frontal Zones; Southern Ocean: Vertical Structure; Synoptic-Scale Weather Systems, Fronts, and Jets; Weddell, Ross, and Other Polar Gyres; Wind**

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ANTARCTIC FUR SEAL

Antarctic fur seals *(Arctocephalus gazella)* are rapidly becoming one of the most abundant seal species in the Antarctic. From a state of near-extinction in the early twentieth century, the Antarctic fur seal has recovered to a population that could now exceed 5 million. The story of this rapid change reflects both the change in human attitudes to the exploitation of marine mammals and changes in the ecosystem of the Southern Ocean, probably also mediated by the impacts of humans on that environment.

The Antarctic fur seal is the only member of the family Otariidae (fur seals and sea lions) that is endemic to the Southern Ocean. (Otariidae belong to the larger taxon Pinnipedia, which includes all seals, fur seals, sea lions, and the walrus.) Antarctic fur seals are one member of a group known as the southern fur seals, eight species that are distributed from the tropics to the sub-Antarctic. The taxonomic status of the southern fur seals is uncertain, and there is almost certainly a degree of introgression between the populations of each species. Antarctic fur seals are known to hybridize with sub-Antarctic fur seals *(A. tropicalis)* at Macquarie Island, and some species are sufficiently similar morphologically that it might be difficult to recognise them from the local species even if they were present on the breeding colonies. However, Antarctic fur seals are distinct in that they have a breeding chronology that differs from other southern fur seal species. Lactation lasts only 4 months compared with around 9 months in the other species of southern fur seals.

The Antarctic fur seal has a circumpolar distribution. Breeding colonies are located mainly on sub-Antarctic islands, but more southerly colonies are found at the South Shetland and South Orkney Islands. Overall, there is little evidence of strong genetic isolation between any of these populations but there may be a weak division between a western region containing the populations of South Georgia and Bouvetøya, which were the probable sources for populations at Marion Island, the South Shetland Islands, and Heard Island, and an eastern region containing the panmictic populations of Îles Kerguelen and Macquarie Island. The latter region may be a result of a pronounced founder effect, or represent a remnant population that survived sealing at Îles Kerguelen.

During the early twentieth century Antarctic fur seals were thought to be extinct, as a result of harvesting of their fur, but in 1922, three juvenile males were recorded at South Georgia by the captain of a sealing vessel. Surveys in the late 1950s showed a small but rapidly increasing population at the western end of South Georgia and the increasing trend appears to have continued ever since. By the early 1990s, the population at South Georgia had reached 1.5 million and colonisation had spread to other islands where rapid rates of increase were also being observed. The population at South Georgia probably represents more than 98% of the world population of the species and is now so large that surveying its size has not been possible in the recent past. However, given the estimated rates of increase through the 1990s, this population could now exceed 5 million seals.

This rapid increase in the number of fur seals is only partly reflective of the present lack of a directed harvest on the species. Changes in the structure of the community of predators that exploit Antarctic krill *(Euphausia superba),* which is an important component of the diet of Antarctic fur seals, is likely to have been another driving force behind the increase in the number of fur seals. Fur seals at South Georgia are likely to consume about 4 million tonnes of krill each year and, before commercial whaling reduced the number of whales, much of this consumption may have been taken up by whales.

Studies of diving behaviour have shown that female fur seals mainly feed within the upper 50 metres of the water column where the water is mixed by the effects of wind and tide. Males dive deeper—to more than 200 metres—and probably have a greater proportion of fish in their diet than females do, especially in winter. The Antarctic fur seals in the eastern region, where krill are either absent or less abundant, feed mainly on lantern fish (myctophids).

Mothers have restricted foraging ranges when they are supporting their pup. The pups remain at the breeding grounds while mothers travel up to 300 km to feed. In winter, when not constrained by having to return regularly to feed their pups, female fur seals travel much further afield. From South Georgia, they will travel south to the ice edge in the northern Weddell Sea and also as far north as the River Plata and the Falkland Islands. Males appear generally to migrate south in the late summer and then follow the ice edge northwards as the winter sets in.

Fur seals are almost certainly predated by killer whales, and some leopard seals appear to specialise on feeding on fur seals close to colonies. Ultimately, the population of Antarctic fur seals, at least at South Georgia, may be regulated by the availability of krill in the vicinity of the island. Large-scale variability in the trophic structure of the Southern Ocean caused by factors such as the El Niño Southern Oscillation is evident in the growth patterns of fur seals and there is accumulating evidence of their sensitivity to interannual variation in krill availability. This sensitivity is now being used as a way of monitoring changes occurring in the marine environment of the Southern Ocean as part of a system for assessing the effects of fisheries on the environment within the Convention on the Conservation of Antarctic Marine Living Resources.

Estimated Sizes and Trends of Antarctic Fur Seal *(Arctocephalus gazella)* Populations

Site	Pup Numbers	Total Population	Year of Census	Mean Annual Rate of Change
Macquarie Island	152[a]		1999/00	increasing
	164[a]		2001/02	(1988/89–1999/2000)[a]
				increasing
Heard Island	248		1987/88	+ 23%
	1,012		2000/01	(1962/63–1987/88)
				+ 20.1%
				(1962/63–2000/01)
McDonald Island	100	300	1979/80	increasing
Îles Nuageuses	2,500[e]	?	1984/85	increasing
(Îles Kerguelen)	5,000		2000	increasing
Courbet Peninsula	2	1,332	1984	increasing
(Îles Kerguelen)	>200	?	1998	increasing
	1,500–1,700	?	2000	increasing
Île de la Possession	67	?	1992/93	+ 21.4%
(Îles Crozet)	234	?	1999/00	(1983–1992)
				+ 16.9%
				(1992–1999)
Marion Island	251[c]	1,205[d]	1994/95	+ 17%
	796[c]	3,821	2003/04	(1988/89–1994/95)
				+13.8%
				(1994/95–2003/04)
Prince Edward Island	400	200	1981/82	increasing
		2000[i]	2001/02	+ 16.2%
Nyrøysa	2,000	>9,501	1989/90	+7.0%
(Bouvetøya)	15,523[c]	66,128	2001/02	(1978/79–1989/90
				+0.1%
				(1996/97–2001/02)
South Georgia	<600,000[e]	2,700,000[f,g]	1990/91	+ 9.8%
		4,500,000 –6,200,000[f,g]	1999/00	(1976/77–1990/91) +6% – 14%
				(1990/91–1999/2000)
South Sandwich Islands	<500	<2,000	1962/63	?
	346		1997/98	stable
South Orkney Islands	<1,000		1970/71	?
South Shetland Islands	9,300		1991/92–1995/96	+ 11%
	10,057[h]		2000/01	(1994/95–1995/96)
				+ 0.9%
				(1995/96–2001/02)
Cape Shirreff (SSSI No32, S.	5,313	21,190	1991/92	+ 14%[i]
Shetland Is.)	8,455		1999/00	(1986/87–1991/92)+ 6%[i]
	8,577		2001/02	(1991/92–1999/00)
				+4.6%[i]
				(1992/93–2001/02)

[a]For populations of both *A. tropicalis* and *A. gazella.*
[b]Corrected for observer undercount.
[c]Corrected for precount mortality.
[d]Recalculated from population values in publication.
[e]Number of breeding females.
[f]Estimated from the number of breeding females.
[g] Standard deviation = 300,000.
[h] Standard error = 140.
[i]Calculated from pup counts.
Data supplied by the Scientific Committee for Antarctic Research.

Antarctic fur seals are colonial breeders. Anybody who visits South Georgia during December will be stunned by the density of seals occupying the available coastline towards the western end of the island. Fur seals are also aggressive animals and are unforgiving towards visitors.

Male fur seals set up territories during early November and females begin to arrive at the breeding grounds during late November. The peak of births occurs at about 7 to 10 December and almost all pups have been born by the end of December. The small, aggressive, inquisitive black-coated pups become the dominant wildlife feature on the beaches.

After giving birth, mothers spend about 6 days with their pups. They are then mated by one of the dominant males holding a territory on the breeding beaches before going to sea to feed for a period of 3 to 6 days. Each mother then returns to feed her single pup for about 2 days and this alternation between feeding at sea and returning to provision the pup continues for a period of about 4 months. Weaning appears to be initiated when the pup abandons the breeding grounds to go to sea during late March or April.

Males hold territory on the breeding grounds for periods of just a day or two to over 30 days. The longer they spend in territory then the more offspring they will sire so there is much competition for territories. This results in overt fighting between males, which has led to advantages for males with large body sizes. Consequently, males are up to 5 times the weight of females (males weigh up to 200 kg whereas females weigh about 40 kg). Males have highly developed neck musculature and, at the beginning of the breeding season, they have an impressive mane of tough hair, which helps to provide some protection against the slashing canine teeth of an opponent.

Owing to their commitment to holding territory, males fast through the breeding season. This means that by late December most males have lost up to one-third of their original body weight. As a result of these stresses, males do not live as long as females (up to 14 years for males compared with over 20 years for females). Many males die as a result of these stresses and large numbers die on the breeding grounds. About half of all these adult males die each year.

Males are also rarely able to breed before they are 7 years of age, whereas females normally begin to breed at 3 years of age. Thereafter, around 80% of females will breed each year. Studies have shown that males often return to breed close to where they were born. This may be because there are advantages to competing with males that are known to one another. Females are probably less likely to return to the location in which they were born; the advantage to females is that pups have a better chance of survival if their parents are not closely related. Once established as a breeder, females return to give birth in the same location in successive years.

Antarctic fur seals have proved to be a highly valuable species for scientific research. Not only is the history of the population recovery a fascinating case study, fur seals are themselves remarkably robust to being the subject of research. Studies of their diving, foraging, diet, behaviour, and population structure have provided insights into the biology of seals. Those who first encounter fur seals are usually overwhelmed by their aggressiveness, but pausing to watch them for a short time will reveal a fascinating world of a species with a complex social structure much of which we still do not understand.

Ian L. Boyd

See also **Bouvetøya; Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Diving—Marine Mammals; Killer Whale; Leopard Seal; Macquarie Island; South Georgia; Sub-Antarctic Fur Seal; Zooplankton and Krill**

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ANTARCTIC ICE SHEET: DEFINITIONS AND DESCRIPTION

The Antarctic ice sheet comprises the vast contiguous coverage of glacial ice that rests on the Antarctic continent and surrounding seas. It is the single largest solid object on the surface of the planet, containing around 90% of the Earth's freshwater and covering around 99.6% of what is generally considered the Antarctic continent. The ice sheet is nourished at its surface by snowfall and frost, which, because of the year-round cold environment, does not melt but accumulates year-on-year. As the surface snows are buried by new snowfall, they are compressed and eventually transform into solid ice, a process that captures a chemical record of past climates and environments. In places, the ice sheet is more than 4500 m thick and the ice in the deepest layers is millions of years old. Glacial flow produces a relentless movement of ice towards the sea, and eventually it either calves away in icebergs or melts directly into the coastal waters. In a sense, the entire Antarctic ice sheet can be considered as an immense conveyor belt, transporting ice from the interior to the coast at a rate of around 2000 billion tonnes per year; a conveyor that is naturally regulated to balance loss by calving and melt with nourishment from snowfall. The continuation of this balance is important because any substantial imbalance would have a noticeable impact on world sea levels.

History of Understanding

During the past hundred years, our understanding of the processes that shape the Antarctic ice sheet has improved, as our ability to map the ice sheet has grown. Only the most primitive mapping techniques were available during the "Heroic Age" of Antarctic exploration, and so most of the maps of the ice sheet that existed even into the 1950s were almost blank. During the International Geophysical Year (IGY; 1957–1958) and the years that followed, extensive scientific traverses were undertaken, which included seismic sounding of the ice thickness and barometric profiling. The maps drawn by Bentley (1964) were based on the very few data collected on traverses, but those maps proved to be a remarkably accurate depiction of the ice sheet and formed the basis of much future work. The next leap forward came as long-range aircraft were equipped with ice-sounding radar in the 1970s, and the joint expeditions undertaken by the Scott Polar Research Institute, the National Science Foundation, and the Technical University of Denmark probably produced the single greatest advance in the understanding of the inner workings of the Antarctic ice sheet. Layering inside the ice sheet observed using radar showed an ordered architecture in the ice sheet that underpins our understanding of glacial flow.

Since that time, satellite data have caused a revolution in our mapping, and our understanding of the ice sheet. Surface elevation, surface temperature, ice flow, and near-surface snow conditions can all be measured from space, and patterns of change in each of these parameters are beginning to emerge. Neither ice sheet thickness nor its internal structure can yet be measured from space, but in recent years feasibility studies have been sponsored by space agencies keen to take this next step in exploring the ice sheet. The mapping and allied experimentation conducted in Antarctica since the IGY have led to a surprisingly thorough knowledge of the ice sheet and its internal working.

Nowadays, thanks to satellite imagery, maps depict the entire Antarctic ice sheet, including its outlying islands—a total area of around 13.7 million square kilometres, much of it featureless tracts of ice. Of this, floating ice shelves comprise around 1.6 million square kilometres. Ice shelves are best considered alongside grounded ice as part of the same ice sheet system. The dynamic interaction between the grounded ice sheet and the ice shelves is a particularly complex one in which ice shelves may provide a buttressing force that stabilizes the grounded ice sheet.

Glaciological Fundamentals

The fundamental concept that underlies the understanding of the Antarctic ice sheet, or indeed any ice sheet or glacier, is related to the interaction between the processes of ice accumulation and those of flow and ablation. Every year ice from new snowfall and hoar frost accumulates on the Antarctic ice sheet. More is deposited around the coast than in the interior, but on average around 190 kg per square metre accumulates each year. For the most part, summer temperatures are insufficient to cause this new snowfall to melt and so it builds up year-on-year—new snow resting on old. Over the millions of years that this process has continued, the ice sheet has thickened and grown, and it would continue to thicken and grow indefinitely if another process did not act in opposition. This process is ice flow, which occurs as ice is subjected to the tremendous forces that exist in the ice sheet. Under these conditions, ice can behave more like an ultraviscous fluid than a solid material (for a detailed description of the processes of glacier movement, see Paterson 1994). On the microscopic scale, slow deformation of crystals occurs, but viewed on the large scale, the ice sheet actually appears to flow. Flow speeds from a few metres per year to a few hundred metres per year are possible due to this deformation, but even greater speeds can occur (more than 1000 metres per year) if the ice begins to slide over its bed. Ice is driven to flow by gravity and, since the ice sheet has a domed topography, flow tends to drive ice towards the edge of the ice sheet where eventually it either melts directly into the sea or calves away in icebergs. The precise interaction between these two processes, nourishment by snowfall and loss through ice flow, has created a self-regulating system of surprising delicacy and precision.

Glaciological Provinces

The Antarctic ice sheet is usually considered in terms of several different provinces, which serve to distinguish dissimilar styles of ice sheet behaviour and to characterize differences in the response to changes. Of these, the East Antarctic ice sheet comprises by far the largest part of the ice sheet, roughly the slice from 30° W, clockwise through the Greenwich meridian, and on to around 165° E. More precisely this is the part of the ice sheet bounded by Filchner Ice Shelf and the Transantarctic Mountains. The East Antarctic ice sheet (EAIS) is generally described as being cold and resting on a bed that is by and large above sea level, or is depressed below sea level by the weight of the ice sheet itself. Much of the ice flow on the interior of the EAIS is slow, and in many areas the ice is frozen to the bed.

This contrasts strongly with the West Antarctic ice sheet (WAIS), the portion occupying the slice from the Transantarctic Mountains through the Siple Coast and Marie Byrd Land and into Ellsworth Land, up to but not including the Antarctic Peninsula. The majority of this ice sheet rests on rock that is substantially below sea level, and would remain so even if the ice sheet were removed. For this reason the West Antarctic ice sheet is described as a "marine ice sheet." The bed beneath the West Antarctic ice sheet is in many areas over 1000 m below sea level—far deeper than most of the world's other continental shelves. The West Antarctic ice sheet is generally warmer, both at the surface and the bed, than its East Antarctic neighbour. In fact, it is close to the melting point over large areas of its bed.

The ice sheet that covers the Antarctic Peninsula is different from either EAIS or WAIS. It consists of much smaller and thinner ice caps that cover the central spine of the peninsula and some of the larger outlying islands. These ice caps drain into the sea through relatively narrow, but steep and fast-moving, alpine-type glaciers. In contrast to WAIS and EAIS, which lose mass primarily through iceberg calving and melt from the base of ice shelves, recent atmospheric warming over the Antarctic Peninsula has had a noticeable impact on its ice sheet. Around ten ice shelves have retreated, and a few (most notably the northern portions of Larsen Ice Shelf) have collapsed spectacularly. Thinning of glaciers has occurred in coastal areas, and some formerly snow-covered islands are now snow-free during the summer.

Together the ice sheets of Antarctica cover more than 99.6% of the entire continent (Fox and Cooper 1994), meaning there is very little exposed rock in Antarctica. In these areas the bed pierces through the ice sheet, or the ice sheet is insufficiently thick to cover the bed, depending on one's point of view. An isolated peak protruding through the ice sheet in this way is called a nunatak, but there are also more extensive mountain areas where many neighbouring outcrops of rock are exposed, including the Dry Valleys of Victoria Land.

An isolated nunatak remains ice-free by virtue of its height above the surrounding ice—the ice-sheet flow is simply diverted around it and it remains protruding above the surface. Understanding how mountain ranges can remain ice-free within an ice sheet is, however, not so simple. If a mountain range were to present a complete barrier to ice flow, the ice sheet would simply thicken until it could surmount the obstacle or flow round it, as is required to achieve a steady-state scenario. And indeed, the ice sheet does cover several mountain ranges (for example, the Gamburtsev Subglacial Highlands in East Antarctica), and in West Antarctica, ice flow is diverted many hundreds of kilometres around the barrier formed by the Ellsworth Mountains. Elsewhere, however, mountain ranges do not present an entirely impenetrable boundary, and where preexisting faults and valleys provide a route, inland ice can flow through the mountain chain in what are called outlet glaciers. The best example of this behaviour is in the Transantarctic Mountains. To an extent, this chain does dam the East Antarctic ice sheet inland and makes it thicker than it would otherwise be, but an entire series of outlet glaciers flow through the range, acting as valves, easing the pressure of ice trying to leave East Antarctica. The outlet glaciers that breach the Transantarctic Mountains are some of the most spectacular on the planet, and glaciers such as Byrd Glacier and David Glacier drain nation-size areas of the East Antarctic ice sheet.

Fast Glacial Flow

Exposed mountain ranges and nunataks are obvious signs of how the flow of the ice sheet is controlled by the underlying bed, but elsewhere the influence of the bed on ice flow is less visible, if no less influential. Even where the ice sheet is several kilometres thick, its flow is strongly influenced by the bed on which it rests. Where geological conditions allow the supply of soft and erodible sedimentary rock, ice flow may be lubricated at the bed by a layer of water-saturated glacial till. This effect allows rivers of fast-flow to develop within a slow-moving part of the ice sheet, and these are called ice streams. Most ice streams are difficult to see from the ground, but many were identified during airborne reconnaissance, and many more have become apparent in recent times. Satellite imagery now allows the mapping of the telltale bands of crevasses that separate ice streams from the slower moving ice, and has revealed a complex pattern of ice streams and tributaries penetrating deep into the continental interior.

More than 40% of the ice leaving the Antarctic ice sheet passes through the twenty largest outlet glaciers and ice streams, and they are thus hugely important in shaping the ice sheet. Furthermore, they are significant in that they appear to transmit the influence of changing ocean conditions over great distances in relatively short periods of time. In addition, ice streams themselves appear to be capable of surprising and quite rapid changes. A little over one hundred years ago, Ice Stream C appears to have stopped streaming, or as it has been described, "switched off." This probably occurred because of a change in the subglacial water pathways, and, in consequence, the part of the ice sheet that once fed Ice Stream C is no longer close to steady state but is thickening at a measurable rate (Joughin and Tulaczyk 2002). For these reasons, outlet glaciers and ice streams have been the focus of a large amount of ice dynamics research in Antarctica in recent times.

The Age of the Ice Sheet

The age of the Antarctic ice sheet is the subject of much debate. It is generally agreed that the East Antarctic ice sheet is much older than the West Antarctic ice sheet, but a great deal of uncertainty still surrounds both ages. The debate concerning the East Antarctic ice sheet centres on some unusual microfossil deposits high in the Transantarctic Mountains, the so-called Sirius Group formations. Depending on the interpretation of those deposits, the age is either put at a little more than 3 million years (implying collapse of the East Antarctic ice sheet during relatively recent Pliocene warm periods) or at some age closer to 20 million years. This greater age coincides with the geological opening of Drake Passage, between the Antarctic Peninsula and South America, which allowed the Antarctic Circumpolar Current to begin, isolating Antarctica and causing a substantial cooling of the climate (for a fuller discussion, see van der Wateren and Hindmarsh 1995).

The West Antarctic ice sheet is probably considerably younger, and may well have been entirely absent in one of the most recent interglacial periods (i.e., at some time since 400,000 years before present), when climate was somewhat warmer than today. Both East and West Antarctic ice sheets have undoubtedly grown and shrunk as Earth passed through glacial cycles, and it is believed that at the last glacial maximum (around 20,000 years ago) the ice sheet extended to the edge of the continental shelf around most of Antarctica. Since then it has retreated and thinned, contributing to many tens of metres of global sea level rise. The question of how much each portion of the Antarctic ice sheet is still responding to climatic changes that occurred more than 10,000 years ago is an open one, but there is clear evidence that some readjustment (i.e., thinning) is still continuing in West Antarctica.

The Changing Ice Sheet

In predicting the future of the ice sheet, these long-term changes in the Antarctic ice sheet need to be considered alongside the responses to contemporary climate change, and the future evolution is likely to be a complex response to many driving forces. Indeed, the shutdown of Ice Stream C is a clear reminder that the Antarctic ice sheet harbours mechanisms that can promote rapid and surprising changes that may have their root not in any climatic forcing, but rather in instabilities in the processes that are normally thought to lead to steady-state conditions.

Recent discoveries made using satellite altimetry data of apparently persistent ongoing surface lowering in the Amundsen Sea sector of West Antarctica have revitalized the debate about a much more

Measured Properties of the Antarctic Ice Sheet from the 5 km Ice Thickness Grid

Parameter	East Antarctica	West Antarctica	Total
Mean ice thickness (m)	2146	1048	1856
Total volume including ice shelves (km^3)	21.8×10^6	3.6×10^6	25.4×10^6
Grounded ice sheet (GIS) volume (km^3)	21.7×10^6	3.0×10^6	24.7×10^6
GIS volume above sea level (km^3)	20.5×10^6	2.1×10^6	22.6×10^6
GIS volume below sea level (km^3)	1.1×10^6	1.0×10^6	2.1×10^6
Global sea level equivalent (m)	52	5	57

Data taken from Lythe et al. 2001.

serious type of change that may govern the fate of the West Antarctic ice sheet as a whole—what has been called the "collapse of the west Antarctic ice sheet" (for a fuller discussion, see Bindschdler and Bentley 2002). This hypothesis arose even when most maps of Antarctica were still blank. Weertman's 1974 theoretical analysis of the junction between an ice shelf and an ice sheet suggested that a marine ice sheet (like the West Antarctic ice sheet) could never be stable, but should always be in the process of change, either growing seaward towards the continental shelf edge or shrinking. The reason a marine ice sheet does not float is because it is thick enough to rest on its bed, and so thinning could lead to floatation and eventually to rapid collapse of the ice sheet. It was therefore argued that much of the West Antarctic ice sheet was vulnerable to collapse, especially the portion of the ice sheet feeding the Amundsen Sea, which rests on a particularly deep bed more than 1000 m below sea level and has only narrow ice shelves to buttress the ice sheet. Although the evidence for potentially rapid retreat of marine ice sheets existing in the record of global sea level is difficult to ignore, the general instability of marine ice sheets is not universally accepted, and several researchers have argued that collapse of WAIS is unlikely (Vaughan and Spouge 2002). So, although the recent surface lowering of the ice sheet in the Amundsen Sea sector was taken by some as evidence for emergent collapse, this is certainly not universally accepted, and the future response of the Antarctic ice sheet as a whole is the subject of many programmes of research.

David G. Vaughan

See also **Antarctic Peninsula, Glaciology of; Climate; Climate Change; Climate Modelling; Drake Passage, Opening of; Filchner-Ronne Ice Shelf; Firn Compaction; Glacial Geology; Ice Ages; Ice Chemistry; Ice Sheet Modeling; Ice Shelves; Icebergs; International Geophysical Year; Lake Ellsworth; Lake Vostok; Lambert Glacier/Amery Ice Shelf; Larsen Ice Shelf; Marie Byrd Land, Geology of; Mega-Dunes; Meteorites; Paleoclimatology; Precipitation; Remote Sensing; Ross Ice Shelf; Snow Post-Depositional Processes; Subglacial Lakes; Surface Energy Balance; Surface Features; Temperature; Thwaites and Pine Island Glacier Basins; Wind**

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ANTARCTIC IMPORTANT BIRD AREAS

Introduction

The global Important Bird Area (IBA) Programme is an initiative of BirdLife International to protect the world's naturally occurring bird populations and habitats. The IBA Programme aims to identify and protect a network of sites critical for the viability of naturally occurring bird populations across their range. Certain sites are, because of the way biodiversity is distributed, disproportionately important for the survival of the species that are found at them. Protection of such sites is a widely adopted and recognized conservation approach.

BirdLife promotes the conservation of all bird species and seeks to conserve biodiversity by preventing extinctions and by maintaining and improving the conservation status of all bird species, particularly globally threatened birds. The IBA Programme is one of the many programs and initiatives of BirdLife. BirdLife is also working for biodiversity conservation through a variety of international mechanisms and conventions including the Convention on Biological Diversity (CBD), the Convention on International Trade in Endangered Species (CITES), and the Convention on Wetlands of International Importance Especially as Waterfowl Habitat (the Ramsar Convention). Collaboration on issues of regional and international importance is a growing trend of the 1990s and beyond, and this list is by no means exhaustive.

The Antarctic IBA Inventory (comprising the terrestrial Antarctic south of 60° S including some

IBA Criteria and Associated Avifauna Breeding in the Antarctic

Category & Brief Description	Relevant Antarctic Species Common Name, Scientific Name
A1. Globally Threatened Species *The site regularly holds significant numbers of a globally threatened species, or other species of global conservation concern.*	gentoo penguin, *Pygoscelis papua* (VU)* macaroni penguin, *Eudyptes chrysolophus* (VU)* southern giant petrel, *Macronectes giganteus* (LR/NT)*
A2. Restricted-Range Species *The site holds species of a restricted range.*	Not used for Antarctic IBA Inventory
A3. Biome-Restricted Assemblage *The site holds species whose distributions are largely restricted to one biome.*	Not used for Antarctic IBA Inventory
A4. Congregations Categories A4(i) and (ii) not used for Antarctic IBA Inventory. *The site holds or is thought to regularly hold:* *(i) over 1% of a biogeographic population of a congregatory waterbird species.* *(ii) over 1% of a biogeographic population of a congregatory seabird or terrestrial species.* *(iii) over 20,000 waterbirds or 10,000 pairs of seabirds of one or more species.* *(iv) Migratory species at bottleneck sites.*	kelp gull, *Larus dominicanus* Antarctic tern, *Sterna vittata* blue-eyed cormorant, *Phalacrocorax atriceps* Antarctic petrel, *Thalassoica antarctica* snow petrel, *Pagodroma nivea* emperor penguin, *Aptenodytes forsteri* Adélie penguin, *Pygoscelis adeliae* chinstrap penguin, *Pygoscelis antarctica* gentoo penguin, *Pygoscelis papua* rockhopper penguin, *Eudyptes chrysocome* Cape petrel, *Daption capense* sub-Antarctic skua, *Catharacta lonngergi* Antarctic skua, *Catharacta maccormicki* greater sheathbill, *Chionis alba* southern giant petrel, *Macronectes giganteus* Wilson's storm petrel, *Oceanites oceanicus* black-bellied storm petrel, *Fregetta tropica* southern fulmar, *Fulmarus glacialoides* Antarctic prion, *Pachyptila desolata*

*IUCN Red List Conservation Status: VU = Vulnerable, LR/NT = Lower Risk/Near Threatened.
http://www.redlist.org

sub-Antarctic islands) commenced in 1999. The Antarctic IBA Inventory is a cooperative effort between BirdLife and the Scientific Committee on Antarctic Research (SCAR) Group of Experts on Birds (GEB, formerly the SCAR Bird Biology Subcommittee, or SCAR-BBS). The Antarctic IBA Inventory is the first practical attempt to take a systematic approach to assessing and prioritizing the need for conservation action at sites by their avian values in the Antarctic, and represents an important preemptive and proactive approach towards the conservation Antarctica's avifauna. The Antarctic IBA Inventory seeks to identify a network of sites in the terrestrial Antarctic based upon their bird values and the application of internationally recognized site selection criteria to existing population data.

What Are IBAs?

The IBA Programme evolved following the compilation of a detailed inventory by the European Union for the identification of prospective sites for designation under the their Wild Birds Directive. This inventory was subsequently updated to become the first official IBA inventory of Europe. Numerous inventories have since been completed or are underway (five regional and forty-eight national as of 2004). The growing recognition of the IBA Programme indicates the substantial contribution it has made to habitat-based conservation on a global scale. The majority of signatories to the Antarctic Treaty (forty of forty-five) have already undertaken or participated in IBA Inventories at national or regional scales.

IBAs are a practical conservation tool that enable the identification of significant sites for the conservation of birds at global, regional, or subregional levels. Seabirds often congregate to breed in high numbers and at high species diversities. Additionally, these sites can be biologically diverse and offer conservation benefits for non-seabird species if they are formally protected. IBAs are selected by the application of internationally uniform criteria that are quantitative and scientifically defensible. These criteria provide a strong foundation for site identification and are a valuable tool for decision makers and managers to use in setting conservation priorities and actions.

Once the initial list of candidate IBAs is compiled, a detailed site description is prepared and circulated for comment. The agreed site accounts, prepared to a standardized format, are then brought together to form an inventory for the country or region. Subsequently the published IBA Inventory can be used to assist in the prioritization of sites for conservation action possible formal protection within the appropriate protected area system. Management and regulation in Antarctica is complicated by unresolved territorial claims, however means for protection do exist within the Antarctic Treaty System and/or under international conventions and agreements. The Antarctic IBA Inventory can assist treaty parties to meet their international obligations to identify and protect a network of sites under Annex V of The Protocol on Environmental Protection to the Antarctic Treaty (the Madrid Protocol).

The Antarctic IBA Inventory

Work on the Antarctic IBA Inventory commenced in 1999. The SCAR-GEB has compiled all available census data of the past 30 or more years on the distributions and abundances of Antarctic breeding birds. These data are the basis for the Antarctic IBA Inventory.

Preliminary Results

The SCAR-GEB and BirdLife cohosted workshops in May 2002 and July 2004 drawing on international expertise to compile and assess published and unpublished data on Antarctic avifauna. The 2004 workshop finalized the list of candidate IBAs. The Antarctic IBA Inventory can be adopted to assist in site prioritization sites for protection within the Antarctic protected area system. For example, sites that meet four IBA criteria may be considered to have a high priority for formal protection.

Completion of the Antarctic IBA Inventory is anticipated for 2007. The Committee for Environmental Protection (CEP) has indicated that upon publication, the results of the IBA Inventory will be assessed to decide how best to implement the required conservation action within the terrestrial Antarctic. The inventory may be adopted by nations with an interest in the Antarctic to assist in setting conservation priorities and to complement the measures already in place within the Antarctic Treaty System. A key factor in the decision-making process is the assessment of threats to identified sites, which will assist in the priority-setting process.

Jane Harris

See also **Adélie Penguin; Antarctic Petrel; Antarctic Prion; Antarctic Tern; Birds: Specially Protected**

Species; Cape Petrel; Chinstrap Penguin; Convention on International Trade in Endangered Species of Wild Flora and Fauna (CITES); Cormorants; Crested Penguins; Emperor Penguin; Gentoo Penguin; Kelp Gull; Macaroni Penguin; Scientific Committee on Antarctic Research (SCAR); Seabird Conservation; Seabird Populations and Trends; Snow Petrel; South Polar Skua; Southern Fulmar; Southern Giant Petrel; Sub-Antarctic Skua; Wilson's Storm Petrel

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ANTARCTIC INTERMEDIATE WATER

A vertical salinity profile taken almost anywhere in the Southern Hemisphere oceans presents a minimum value within the upper 1000 meters of the water column. Throughout the Southern Hemisphere, this subsurface low salinity layer forms a coherent tonguelike distribution extending from near the surface at high southern latitudes to depths of about 1000 meters at midlatitudes. This water mass, first detected in the South Atlantic and described by German and British oceanographers during the first half of the twentieth century, is referred to as Antarctic Intermediate Water (AAIW; Deacon 1933; Wüst 1935). The northward salinity increase at the salinity minimum (S_{min}) core is due to a combination of mean northward flow and mixing with the saltier waters found in the layers above and below. Since the meridional distribution of sources of heat, freshwater and other properties over the Earth is uneven, by redistributing these properties across latitude bands, such meridional flows play a key role on the climate system. The observation of the S_{min} at the surface near the northern edge of the Antarctic Circumpolar Current suggests that the water mass acquires its characteristics (is formed) at this location. In the process of AAIW formation, water parcels sink and transfer properties and dissolved gases from the near surface layers, where they are in equilibrium with atmospheric concentrations, to intermediate depths, where they can be stored away from the atmosphere for periods of several years to several decades. Thus, AAIW also contributes to the absorption of carbon dioxide and other atmospheric constituents into the ocean interior.

Water Mass Properties

Properties on the low salinity layer vary substantially between ocean basins. These variations suggest either differing property concentrations in the formation regions and/or distinct flow patterns and resident times in different oceans. The mean properties of the AAIW S_{min} in the latitude band between 30 and 40° S are summarized here.

Depth

In the three Southern Hemisphere oceans, the core of the AAIW, as represented by the S_{min} layer, is found at the sea surface between 50°–60° S, deepens northward near 30°–40° S, and then rises again to 750–500 meters towards the Equator. Although the salinity of

Mean Properties of the Salinity Minimum Core in the Latitude Band Between 30° S and 40° S

Basin	Potential Temperature (°C)	Salinity	Potential Density Anomaly (kg/m^3)*	Dissolved Oxygen (mL/L)
Atlantic	3.85	34.25	27.20	5.4
Indian	4.54	34.41	27.26	4.6
Tasman Sea	5.18	34.46	27.23	4.1
W. Pacific	5.15	34.42	27.20	4.4
E. and C. Pacific	5.01	34.29	27.11	5.0

*Potential density anomaly is calculated after removing the pressure effect and is given in kg m^{-3} after subtracting 1000 kg m^{-3}.

the layers above and below the S_{min} are saltier than in the Indian and Pacific oceans, the salinity minimum layer in the Atlantic Ocean can be detected beyond 20° N. In the Pacific Ocean there is an analogue to AAIW formed at high Northern Hemisphere latitudes, the North Pacific Intermediate Water, and both S_{min} layers converge near the equator. In contrast, in the Indian Ocean, the S_{min} is confined to south of 10° S. On average, north of 40° S the S_{min} layer lies at about 800 m in the South Atlantic sector and about 1200 m in the southwestern Indian Ocean. The S_{min} core in the South Pacific rises from about 900 m in the western basin to less than 600 m off southern Chile.

Potential Temperature

To compare temperatures from water at different depths, it is convenient to remove the pressure effect, which contracts the water parcels and slightly increases their *in situ* temperature. For this purpose we use the temperature the water attains when displaced to the sea surface without exchanging heat with its surroundings, referred to as potential temperature (θ). The coldest AAIW is observed in the western South Atlantic (θ ~ 3.8°C). Potential temperature rises eastward across the Atlantic and Indian ocean sectors of the Southern Ocean, reaches 5.2°C in the Tasman Sea and decreases further east to about 5°C in the eastern South Pacific.

Salinity

The lowest salinity (S ~ 34.2) at the S_{min} core is found in the western South Atlantic. Within the South Atlantic basin salinity increases slightly eastward. The saltiest S_{min} is found in the southwestern Indian Ocean and the Tasman Sea (S higher than 34.4). In the South Pacific salinity at the S_{min} core decreases eastward from ~34.42 east of New Zealand and in the eastern South Pacific attains values close to those observed in the western South Atlantic.

Dissolved Oxygen

At or slightly above the core of AAIW salinity minimum, a dissolved oxygen maximum is frequently found. Dissolved oxygen (O_2) primarily enters the ocean from the atmosphere, thus, though it is not strictly conservative due to biological activity, a relative maximum is a signature of more recent layer "ventilation" at the sea surface. The highest dissolved oxygen concentrations at the S_{min} layer (O_2 ~ 5.4 mL/L) are observed in the western South Atlantic. Dissolved oxygen concentrations decrease eastward across the South Atlantic and South Indian Ocean, reaching a minimum in the Tasman Sea (O_2 ~ 4.1 mL/L) and increase further east to ~5 mL/L in the eastern South Pacific.

Potential Temperature-Salinity Distributions

In the Polar Front Zone, south of the Sub-Antarctic Front, there is a low salinity surface layer that connects to the AAIW S_{min} observed farther north. In the subtropical band the circumpolar salinity minimum is observed within the 3.5°C–5.5°C potential temperature range. The South Atlantic presents the lowest S_{min} layer at about 4°C and 850 m. The South Indian presents the saltiest and deepest (~1300 m) AAIW. In the South Pacific the salinity at the S_{min} is ~34.35 and is not as well defined as in the Atlantic and Indian oceans, because the layers above and below are comparatively fresh. Large excess precipitation over evaporation is presumably responsible for the lower salinity of the upper layers in the southeast South Pacific, while mixing has reduced the salinity of deep waters.

Water Mass Formation

There is no universally accepted theory of AAIW formation. The classical view (Deacon 1933; Wüst 1935) ascribes the low salinity layer to sinking along constant density surfaces from the region near the Polar Front Zone, from where the water mass spreads northward. Sverdrup (1940) suggested that AAIW formation is associated to convergence and subsequent sinking of upper layer waters induced by meridional structure of the wind field over the Southern Oceans. The sources for AAIW are mixtures of Antarctic Surface Water and Circumpolar Deep Water upwelled along the axis of the Antarctic Circumpolar Current. Alternatively, it has been suggested that AAIW is a product of relatively deep convection in the Sub-Antarctic Zone, north of the Sub-Antarctic Front. The latter water mass is referred to as Sub-Antarctic Mode Water (SAMW, McCartney 1977). Late winter convection forms relatively thick layers of quasi-homogeneous temperature, salinity, and density. These layers are referred to as thermostads (e.g. are quasi-homogeneous in temperature) or pycnostads (e.g. are quasi-homogeneous in density). Thus, from a volumetric point of view, the products of convection are modes, from which the water mass name is derived. Mode waters are also found in the subtropical and subpolar oceans in the Northern Hemisphere. After convection mode waters flow along constant density surfaces and are capped by the warm, salty upper layer waters characteristic of the midlatitude oceans. Mode water properties depend on the initial temperature and salinity of the surface layer and on the sea-air exchanges of heat and freshwater through the balance between evaporation and precipitation. The coldest, freshest, and densest variety of SAMW is found in the eastern South Pacific. Density progressively decreases eastward as temperature and salinity increase. Because the S_{min} observed in the western South Atlantic is fresher and denser than the densest southeast Pacific SAMW, an Antarctic influence from the Polar Front Zone in the vicinity of Drake Passage and further modifications by sea-air interactions within the southwest Atlantic have been suggested. These AAIW transformations are also apparent in global ocean circulation models. Thus, southwest Atlantic AAIW appears to be formed by a complex combination of the mechanisms described above. Warmer and saltier SAMW is formed throughout the South Indian and western South Pacific oceans, but these waters are significantly lighter than AAIW ($\sim$26.8 kg m^3) and therefore ventilate density horizons shallower than the salinity minimum layer.

Circulation

The most vigorous element of the circulation at the core of AAIW is associated to the circumpolar flow within the Antarctic Circumpolar Current. This flow, primarily along the Sub-Antarctic Front, is a significant conduit of exchange between ocean basins. Farther north, within each ocean basin, AAIW describes a large-scale counterclockwise loop. These flow patterns, also known as gyres, are generated by the curl of the wind stress at midlatitudes, caused by the opposing directions of the trades and the westerlies. AAIW flows northward on the eastern side of each basin, turns eastward at about 20° S and southward along the western boundary. The flow along this path is not uniform; velocity increases as the water approaches the western boundary and is most intense along the so-called western boundary currents that carry AAIW back southward. This asymmetry in the circulation is also reflected on the depth of the AAIW layer, which lies deeper in the western side of the oceans. In the Southern Hemisphere the western boundary currents in the Atlantic, Indian, and Pacific oceans are the Brazil, Agulhas, and East Australian currents, respectively. These are regions of enhanced turbulence associated to eddies and meanders where intense mixing of the different varieties of AAIW is observed. The recirculated AAIW observed at the poleward extensions of the western boundary currents are generally saltier and lower in dissolved oxygen than near the eastern boundary, since they have been subject to vertical mixing with the saltier layers above and below for a longer period of time. Leakage of Indian Ocean AAIW into the eastern South Atlantic via the Agulhas Current leads to increased salinities at the S_{min}. In the western South Atlantic and South Pacific oceans AAIW from the Sub-Antarctic Front flow northward along the western Argentine Basin (the Falkland/Malvinas Current) and the eastern flank of the Campbell Plateau, respectively. The Falkland Current is a substantial source of nutrients that sustains the development of phytoplankton and fishery along the eastern edge of the Patagonian shelf. These waters mix with the recirculated varieties of AAIW flowing in the opposite direction but there is no evidence of northward penetrations of AAIW along the western boundary below the western boundary currents southward extensions as originally thought.

The marked northward penetration of AAIW in the Atlantic is presumably a response to the so-called Global Thermohaline Circulation. In this large-scale flow, dense, salty water sinks to 2000–3500 m depths in the northern North Atlantic, flows southward, and is exported to the Indian and Pacific oceans. Export of deep waters is balanced by a return flow through the South Atlantic and into the North Atlantic, mostly at shallower levels. This return flow is composed by AAIW and thermocline waters. Thus, northward flow of AAIW in the Atlantic is enhanced by this large-scale meridional cell.

Variability

Variability of AAIW can be attributed to a combination of changes in the sea-air heat and freshwater exchanges at the regions of formation, variations in the thermal and haline characteristics of the source water, and variations in the circulation patterns. These processes can lead to changes in water mass properties in a variety of time and spatial scales. Once the water sinks its properties change by mixing with the surrounding waters, but mixing in the ocean interior is weak and the water retains the signature of the formation conditions. Thus, away from the sea surface, water mass variability provides a record of changes at the sites of formation and may serve as indicators of climate variability. Time series are only available at few locations in the Southern Ocean, and knowledge of the variability is mostly based on comparison of the thermal and haline characteristics determined from hydrographic observations occupied at different times. Within these limitations, changes in the AAIW and SAMW properties in the Southern Ocean are now relatively well documented. In the period from the early 1960s to the late 1980s, AAIW and the denser varieties of SAMW throughout the South Indian Ocean and in the Tasman Sea have freshened and cooled. Freshening is consistent with an increased excess precipitation over evaporation in the region of AAIW formation and has been interpreted as a signature of an increase in the strength or intensity of the hydrological cycle. Similarly, warming of the lightest varieties SAMW is associated to long-term warming of the surface waters in the formation region north of the Sub-Antarctic Front. This observation is consistent with predictions of global warming associated to increased atmospheric CO_2. Observations in the South Indian Ocean, including data collected in 2002, suggest that after the late 1980s the warmer varieties of SAMW have become saltier, almost entirely reversing the effect of freshening observed in the previous decades, while the salinity of the colder SAMW continued decreasing. Given the few observations available in the Southern Hemisphere, it is not yet possible to determine whether the observed changes in water mass properties are related to climate trends or to decadal oscillations.

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See also **Antarctic Surface Water; Atmospheric Gas Concentrations from Air Bubbles; Circumpolar Current, Antarctic; Circumpolar Deep Water; Polar Front; Southern Ocean Circulation: Modeling; Southern Ocean: Climate Change and Variability; Southern Ocean: Fronts and Frontal Zones; Southern Ocean: Vertical Structure; Thermohaline and Wind-Driven Circulations in the Southern Ocean**

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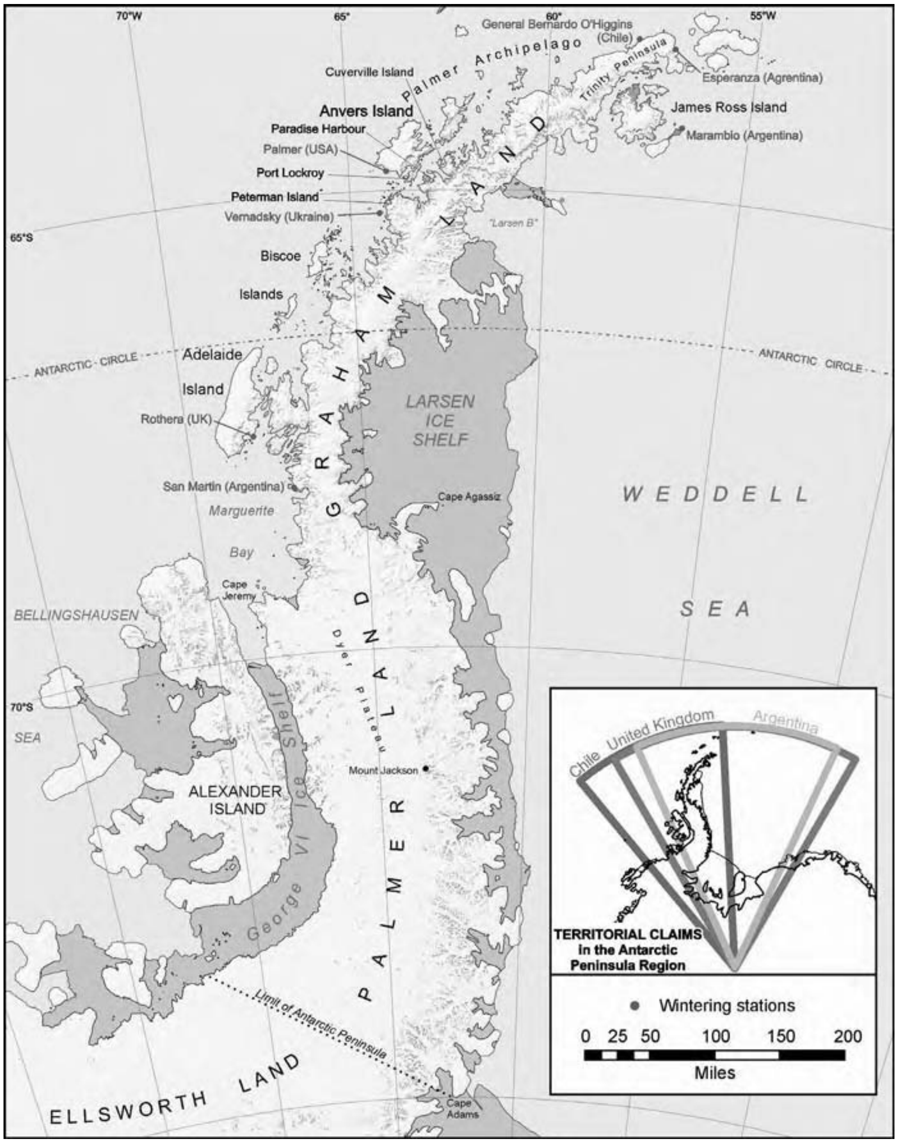

The Antarctic Peninsula.

ANTARCTIC PENINSULA

The Antarctic Peninsula stretches from the continent towards South America in a north to north-easterly trending arc. At its most northerly point (57°18′ W, 63°13′ S), it is 620 miles (999 km) from Cape Horn, separated by the Drake Passage. It is 777 miles (1250 km) long, and ranges from 178 miles (287 km) wide at its most southerly point to 15 miles (24 km) wide near its northern extremity on the Trinity Peninsula. Its southern boundary stretches from Cape Adams westwards, to a point at 73°24′ S, 72°00′ W. The mainland peninsula covers an area of approximately 79,000 square miles (127,000 km^2).

The Antarctic Peninsula separates the Weddell Sea, to the east, from the Bellingshausen Sea to the west. The northern part (north of a line between Cape Agassiz and Cape Jeremy) is Graham Land, and the southern part is Palmer Land. The Antarctic Circle runs through the southern half of Graham Land, at approximately 66°30′ S.

The landscape is dominated by rugged coastline and a dramatic mountain range running along the length of the peninsula, interspersed with a number of ice-covered plateaus, the largest of which is the Dyer Plateau, in Palmer Land. The highest peak is Mount Jackson, at 10,453 ft (3184 m) above sea level, located in central Palmer Land. Approximately 2.6% of the mainland peninsula is free of ice and snow during the austral summer. Rivers or lakes on the mainland peninsula are few, and are mostly restricted to the Trinity Peninsula.

Numerous glaciers run either directly into the sea or feed major ice shelves, the largest of which is the Larsen Ice Shelf, which bounds most of the eastern side of the peninsula. Over the past six decades, 87% of the marine glaciers in the peninsula region have retreated, by on average 50 m a year. Over a similar period, there has been a progressive retreat of most ice shelves, including the Larsen B, which collapsed dramatically in 2002.

Major offshore island groups include the Palmer Archipelago and the Biscoe Islands. The largest individual islands fringing the peninsula are Adelaide Island and Alexander Island, which is separated from the mainland by the permanently frozen George V Sound.

The climate across the peninsula region varies considerably. The west coast experiences the warmer, maritime Antarctic climate. The east coast has the colder, continental climate. In the north, average monthly temperatures exceed zero in the summer. Annual average temperatures have risen by nearly 3°C in the central and southern parts of the west coast of the peninsula over 50 years. This is a larger rise than elsewhere in the Southern Hemisphere.

Due largely to its warmer climate and ice-free ground, the western side of the peninsula (including offshore islands) between approximately 64° and 68° S is biologically richer and far more diverse than the rest of the continent. Sixteen species of seabird breed here, including four species of penguin (gentoo, Adélie, chinstrap, and emperor). Five species of seal (crabeater, elephant, fur, leopard, and Weddell) haul out on the beaches and ice floes, and Ross seals are occasionally sighted on the eastern side of the peninsula. There are no breeding terrestrial mammals. Only one species of higher insect is found, otherwise this simple macroscopic invertebrate ecosystem is dominated by mites and springtails. A much greater diversity is found amongst lower invertebrates.

The terrestrial flora comprises about sixty-seven species of moss, nine species of liverwort, and 265 species of lichen, as well as Antarctica's only two flowering plants—Antarctic pearlwort *(Colobanthus quitensus)* and Antarctic hairgrass *(Deschampsia antarctica)*.

This region contains thirteen Antarctic Specially Protected Areas, which have been adopted under the Antarctic Treaty System, as well as eighteen Historic Sites and Monuments.

The first sighting of the mainland peninsula is claimed by the Russian naval Captain Fabian Gottlieb von Bellingshausen, the British naval Captain Edward Bransfield, and the US sealer Nathanial Palmer, all in 1820. The history of this region, covered extensively elsewhere in this encyclopedia, was principally defined by sealing, whaling, exploration, and scientific discovery.

The peninsula was first claimed by the UK by means of the Royal Letters Patent of 21 July 1908 (amended by the Royal Letters Patent of 28 March 1917) as part of the Falkland Island Dependencies. Later, the Order of Council of 26 February 1962 established British Antarctic Territory as a separate colony. Overlapping counterclaims are held by Chile and Argentina. Territorio Chileno Antártico was established by Presidential Decree of 6th November 1940. In 1943, Argentina stated its sovereign rights over this sector of Antarctica, extending and formalising it as Antártida Argentina in 1947. All territorial claims were laid in abeyance by the Antarctic Treaty (1961).

Mapping and survey of the peninsula has been undertaken principally by the UK from 1944 to the present date. Major aerial survey expeditions include Operation Highjump 1946–1947 (USA), the Ronne Antarctic Research Expedition 1947 (USA), the Falkland Islands Dependency Aerial Survey Expedition in 1956–1957 (UK), and the US Navy TriMetrogon Aerial survey, mainly between 1966 and 1968. Mapping by other Antarctic operators exists locally and around specific sites.

There are seven wintering stations operated by five nations in this region, although only one, Esperanza (Argentina) is located on the mainland peninsula. In addition, there are some ten summer-only stations. The number occupied varies from year to year, and some would appear to have been abandoned. Most stations are resupplied by ice-strengthened vessels during the austral summer. Hard-rock airstrips are located at Rothera Research Station (UK) and Marambio (Argentina). Scientific facilities and programmes vary from globally important to basic, and in some cases, rudimentary.

Due to its relative ease of access, the peninsula is also the busiest region of Antarctica for tourism. The most visited locations include Port Lockroy, Paradise Harbour, and Cuverville and Peterman islands.

Rod Downie and Peter Fretwell

See also **Adélie Penguin; Aircraft Runways; Antarctic Fur Seal; Antarctic Peninsula, Geology of; Antarctic Peninsula, Glaciology of; Antarctic Treaty System; Antarctica: Definitions and Boundaries; Bellingshausen, Fabian von; Bransfield Strait and South Shetland Islands, Geology of; Chinstrap Penguin; Climate Change; Crabeater Seal; Emperor Penguin; Falkland Islands and Dependencies Aerial Survey Expedition (FIDASE) (1955–1957); Gentoo Penguin; Geopolitics of the Antarctic; Ice Shelves; Larsen Ice Shelf; Leopard Seal; Liverworts; Mosses; Palmer, Nathaniel; Parasitic Insects: Mites and Ticks; Protected Areas within the Antarctic Treaty Area; Ronne Antarctic Research**

Expedition (1947–1948); Russian Naval (*Vostok* and *Mirnyy*) Expedition (1819–1821); Sealing, History of; Southern Elephant Seal; Springtails; Sub-Antarctic Islands, Geology of; Tourism; United States Navy Developments Projects (1946–1948); Vegetation; Weddell Seal

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ANTARCTIC PENINSULA, GEOLOGY OF

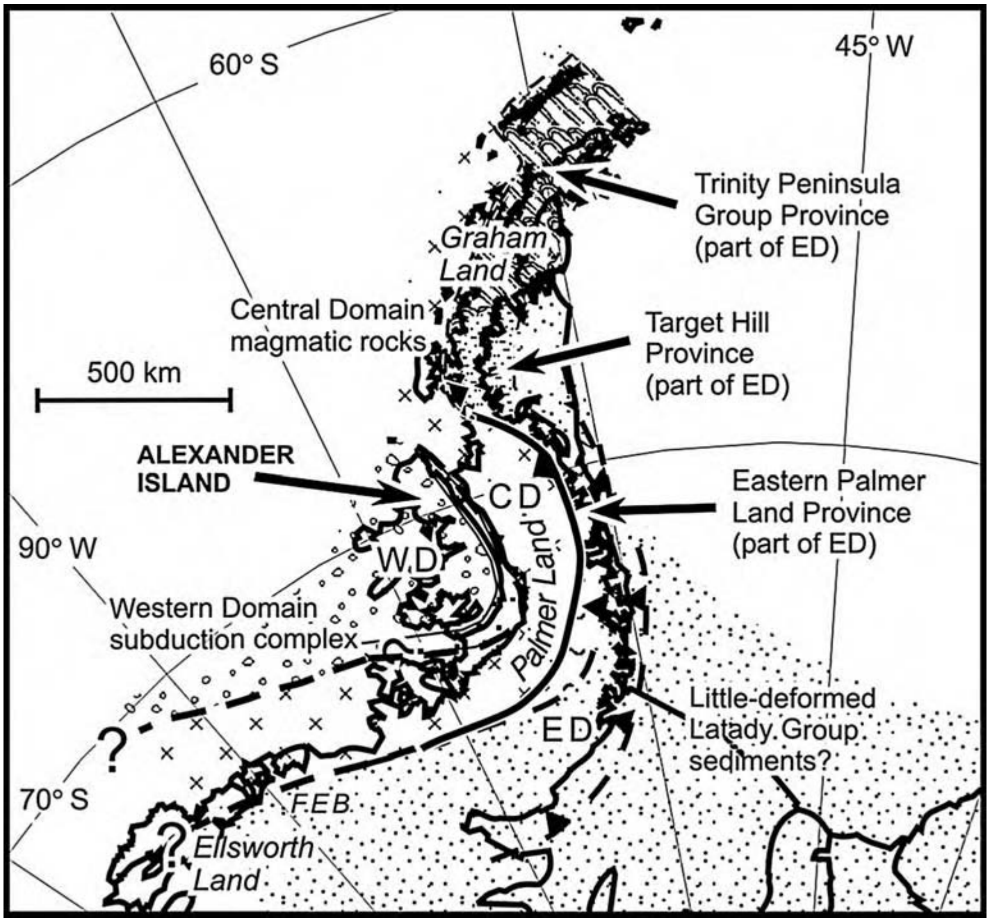
The Antarctic Peninsula is a chain of rugged mountains, up to 4190 metres high, that is divided geographically into a northern and southern portion, Graham Land and Palmer Land respectively. Graham Land lies north of 69° S and is a relatively narrow peninsula with many small offshore islands, whereas Palmer Land is higher and broader with a single large island to the west, Alexander Island.

The geology of the Antarctic Peninsula has been extensively studied since earliest explorers collected rock samples whilst visiting the area in the late 1800s and early 1900s. It is interpreted as the deeply eroded routes of a Mesozoic magmatic arc that formed on Palaeozoic or older continental basement rocks from eastward subduction of proto-Pacific and Pacific Ocean lithosphere. It contains a deeply dissected volcanic province and in some places broad subduction-accretion complexes with thick sedimentary sequences flanking both sides of the peninsula from inverted fore and back arc basins. Eastward subduction of oceanic crust beneath the peninsula occurred from at least the Triassic to Tertiary times, and may have started as early as the mid-Palaeozoic. Subduction ceased due to a series of ridge crest-trench collisions the age of which decreased progressively northwards along the peninsula, occurring off southern Alexander Island between 53.5 ± 1 and 45 ± 3 Ma, and off northern Alexander Island at 32 ± 3 Ma. Plate convergence is still continuing off the South Shetland Islands and South Scotia Ridge where the remnant Drake Plate is subducting beneath the northern tip of the Antarctic Peninsula.

The extent to which the peninsula represents a near complete Mesozoic arc-trench system that formed *in situ* during continuous subduction has been considered; an alternative interpretation has recently been published by Vaughan and Storey (2000) suggesting a new terrane model involving the possible accretion of suspect terranes during the Mesozoic development of the peninsula. The new model is based on the discovery of a major fault zone in the magmatic arc in Palmer Land, which is used to divide the peninsula into geological domains. Two and possibly three separate terranes may have collided resulting in mid-Cretaceous deformation referred to as the Palmer Land orogeny. However, the extent to which terrane accretion has occurred is currently uncertain and does not detract from the basic description of the tectonic elements given here starting with the oldest units.

Basement

The term *basement* is used here to describe the older pre-Mesozoic rocks into which the Mesozoic magmatic arc was emplaced. Its identification has proved difficult due to the intensity of the Mesozoic activity that has reworked or overprinted earlier events and due to the isolated nature of the outcrops. However, its presence and history is extremely important as it provides a window into the evolution of the peninsula prior to the extensive Mesozoic activity. It is now known that the Antarctic Peninsula has a fragmentary geological record that stretches back at least to Cambrian times. Separate Palaeozoic elements have been identified following extensive reliance on precise geochronological dating.



Geological map of the Antarctic Peninsula showing relevant place names.

Palaeozoic Granites and Gneisses

Orthogneisses with protolith ages of circa 450–550 Ma crop out in small areas of eastern Graham Land and northwestern Palmer Land, and paragneisses that are no older than late Cambrian form the basement to Triassic granites and granodiorites in eastern Palmer Land. Carbon and oxygen stable isotopic data on pre-Late Triassic marbles in northeastern Palmer Land suggest marine carbonates are present within the paragneisses. A few small granite bodies are present in eastern Graham Land at Target Hill circa 400 Ma and are present elsewhere on the peninsula as clasts in conglomerates. Locally the Palaeozoic basement underwent metamorphism, migmatisation, and granite emplacement during Carboniferous (c. 325 Ma) and Permian (c. 260 Ma) times. The extent to which these events represent a long-lived magmatic arc extending back into the Palaeozoic cannot be established based on the scarcity of data but they provide a unique window into earliest magmatic and metamorphic events that are recorded in the peninsula.

Palaeozoic Sedimentary Sequences

As well as and in contrast to the Palaeozoic igneous and metamorphic events mentioned above, two unique sedimentary successions, the Fitzgerald and Erewhon beds, have been preserved and discovered within central Palmer Land. The Fitzgerald Beds are cratonic quartzites of possible Lower Palaeozoic age, whereas the Erewhon Beds are Permian quartzose sedimentary rocks that contain the Gondwana Glossopteris fauna. Sandstone detrital modes indicate a minor arc-derived component for the Erewhon Beds. These are undoubtedly typical Palaeozoic Gondwana cover sequences that serve to link at least this part of the peninsula with the rest of Gondwana and suggest that it was not part of the active margin of Gondwana at that time.

The Trinity Peninsula Group is a thick Palaeozoic sedimentary succession that crops out in Graham Land at the northern end of the Antarctic Peninsula and comprises siliciclastic mudstone, siltstone, sandstone, and rare coarser deposits that are metamorphosed to low-grade. Being poorly fossiliferous, its age range is not well constrained but it was probably deposited between the Carboniferous and Triassic. Its tectonic setting is equally enigmatic although most authors agree that it was deposited in a forearc accretionary setting with derivation from arc and continental high grade terranes. The deformational style of the group is consistent with deformation in an accretionary setting.

Mesozoic Magmatic Arc

Mesozoic magmatic rocks are present throughout the Antarctic Peninsula including offshore islands and include the Antarctic Peninsula Batholith and deeply dissected volcanic rocks referred to as the Antarctic Peninsula Volcanic Group.

Antarctic Peninsula Batholith

Plutonic rocks that form the Antarctic Peninsula Batholith were emplaced between c. 240 Ma and 10 Ma, a period which spans the breakup of Gondwana and subsequent segmentation of West Antarctica. The batholith is 1350 km long by less than 210 km wide and intrudes the basement gneisses, coeval volcanic rocks, and fore and back-arc sedimentary rocks. The activity was virtually continuous although there appears to be significant early Jurassic (199–181 Ma) and late Jurassic to early Cretaceous (156–142 Ma) gaps in intrusive activity that may correspond to episode of arc compression. There was a Cretaceous peak of activity that started at 142 Ma and waned during the late Cretaceous. The distribution of the magmative activity varied in time and space throughout the length and breadth of the peninsula and was related to the tectonic history of the arc system through time.

Emplacement of Triassic and Early Jurassic plutons and migmatisation of basement gneisses were widespread in northern Palmer Land at this time (c. 230–200 Ma). The earliest plutons are peraluminous granites, with s-type characteristics that formed largely by melting of local paragneissic basement. By 205 Ma, metaluminous, I-type granodioroite were also being generated. It is speculated that this magmatism may represent the initiation of subduction along the Gondwana margin. During the Jurassic period, magmatism was extensive and corresponded with the breakup of Gondwana. It included extensive silicic volcanism and associated subvolcanic plutonism.

Cretaceous and younger plutons were emplaced along the length of the batholith as a result of east-directed subduction of proto-Pacific oceanic crust beneath the Antarctic Peninsula. These range in composition from gabbro to granodiorite and are dominated by metaluminous, calcic, silicon-oversaturated compositions. Unequivocal subduction related plutonism was initiated by c. 142 Ma, and was most voluminous and widespread between 125 and 100 Ma. The Tertiary part of the batholith is restricted to the west coast of the Antarctic Peninsula, signifying a major westwards jump in the locus of the arc. Subduction and its associated magmatism ceased in the Antarctic Peninsula between circa 50 Ma and the present day, following a series of northward-younging ridge-trench collisions. Subduction continues in one small segment off the South Shetland Islands where the remnant Drake plate is sinking beneath the northern tip of the Antarctic Peninsula. Related back arc extension and associated volcanism is occurring in Bransfield Strait and on Deception Island.

Antarctic Peninsula Volcanic Group

The associated Antarctic Peninsula Volcanic Group dominantly comprises subaerially erupted lavas and volcaniclastic deposits, including numerous ignimbrites. It is up to 3 km thick in places and comprises a calc-alkaline suite consisting mostly of basalts, basaltic andesites, abundant andesites, dacites, and rhyolites. Contacts normally reveal plutons intruding volcanic rocks with unconformable relationships being rare. Dykes cutting plutonic and volcanic rocks are common throughout the Antarctic Peninsula. Most of the dykes are near vertical, up to 10 m wide, mafic, with chilled margins and in places intrude along normal or strike slip faults. They form local parallel swarms, but there is no regionally consistent trend, and cone sheets arrays near intrusions are locally developed. Syn-plutonic dykes are common.

Many of the volcanic rocks exposed on the western side of the Antarctic Peninsula are Cretaceous in age and have intermediate compositions whereas silicic volcanic rocks occur irregularly on the eastern side of the peninsula and are typically middle Jurassic in age. The silicic volcanic rocks are dominated by rhyolitic ignimbrite flows, with individual units up to 80 m in thickness. Rhyolite lava flows, air-fall horizons, debris flow deposits, and epiclastic deposits are volumetrically minor, occurring as interbedded units within the ignimbrite succession.

Eastern Palmer Land Shear Zone

East of the central spine of Palmer Land, a major strike-slip shear zone deforms plutonic, metamorphic, metasedimantary, and metavolvcanic rocks. The shear zone is a complex of ductile and brittle-ductile, reverse and dextral-reverse shears up to 15 km across strike and generally at amphibolite facies. In its northern part, the shear zone forms ductile, reverse, or dextral-reverse mylonite whereas in its southern part, a complex breccia zone crops out. The tectonic significance of this feature is uncertain. It has been used to define the boundary between newly identified geological domains and interpreted as a suture along which an allochthanous central terrane may have collided with the Gondwana margin in mid-Cretaceous times. Although this model remains to be tested for the Antarctic Peninsula, it is consistent with other parts of the Pacific margin of Gondwana.

Fore Arc Region

Accretionary subduction complexes and forearc basin sequences are present to varied extents along the western margin of the Antarctic Peninsula Mesozoic magmatic arc.

Accretionary Complex

The LeMay Group of Alexander Island on the western side of the Antarctic Peninsula is an unusually wide accretionary complex compared with the remainder of the palaeo-Pacific margin of Antarctica. The exposed part of the complex is up to 300 km wide and is preserved in an embayment of the arcuate Mesozoic magmatic arc. It is comprised of deformed trench-fill turbidites, trench slope sequences, and allochthonous slivers of ocean-floor and ocean-island igneous and sedimentary rocks. The age of the complex is constrained by the presence of an Early Jurassic ammonite from accreted tuffs within an ocean island sequence, and by Late Jurassic to Early Cretaceous and mid-Cretaceous radiolarian from accreted cherts. All of the ages are from allochthonous units, which place maxima on the ages of accretion in those parts of the prism where they are exposed. The ages show a pattern of younging towards the margin consistent with an accretionary prism model. On the eastern side, the complex is unconformably overlain and in faulted contact with a forearc basin sequence, which places a minimum Middle Jurassic age on this part of the prism. The complex may have developed by the accumulation of docked exotic terranes in a preexisting embayment along the palaeo-Pacific margin, or alternatively by long-lived subduction and accretion along this segment of the margin. In the latter case, subsequent oroclinal bending of the magmatic arc may account for the unusually wide complex now preserved in the arcuate embayment of the margin.

Fore Arc Basin

The Fossil Bluff Group is a thick (up to 7 km) fore arc basin sequence that sits unconformably on and is in faulted contact with the accretionary complex rocks of Alexander Island. It consists dominantly of silty mudstone, with significant amounts of sandstone and conglomerate. Palaeocurrent and provenance analysis indicate that the bulk of the unit was derived from the volcanic arc to the east, although there is a minor component of accretionary complex-derived material mainly in the western parts of the group. Deposition of the group spanned Mid-Jurassic (Bathonian) to Albian times and has been divided into two major stages of basin development punctuated by short duration tectonically induced events. The oldest Selene Nunataks and Atoll Nunataks formations, exposed on the western side of the basin, record the first stage, the transition from trench-slope to fore-arc basin sedimentation. These units were derived from the accretionary complex rather than the volcanic arc. All other strata in the basin are part of the second stage fore-arc basin sedimentation and form a large-scale, shallow upward cycle of Kimmeridgian to Albian age.

The sequence was deformed by oblique north-northwest to south-southeast trending folds with an associated weak cleavage. The geometry of a range of related structures including bifurcating arrays of sandstone dykes, bedding parallel slip, conjugate normal faults, and steep dextral normal oblique faults have been used to suggest that basin inversion involved dextral transpression.

Magmatic History

The Mesozoic fore arc region on Alexander Island was intruded in Late Cretaceous to Early Tertiary times (80-52 Ma) by subduction-related magmatic rocks, the youngest part of the Antarctic Peninsula Batholith. The rocks occupy what was a fore-arc position 100–200 km trenchward of the main arc on the Antarctic Peninsula. The magmatic rocks become younger northward along the length of the island.

Back Arc Region

Thick sedimentary successions developed within the Larsen and Latady basins on the eastern back arc side of the Antarctic Peninsula Mesozoic magmatic arc during the Jurassic and Cretaceous periods. The earliest of these was probably that on the southeastern margins that was to become the site of accumulation of the Middle-Late Jurassic Latady Formation.

The Latady Formation is a poorly known folded sequence of Jurassic fossiliferous shallow marine to terrestrial sandstones to mudstones. The succession comprises black and grey slate, siltstone, and mudstone with subordinate sandstone and coal; conglomerate is rare. It is estimated to be several kilometers thick. There appears to be a transition in depositional environment from a terrestrial setting near the axis of the peninsula (magmatic arc) into a truly marine environment to the southwest. Nonmarine sedimentary rocks, containing abundant plant fossils and thin coal beds, interdigitate with air-fall and ash-flow tuffs, lava flows, and volcanic breccias at the basin margin. The nonmarine deposits pass laterally through shallow marine, possibly deltaic rocks into open marine deposits. On the basis of locally abundant marine faunas, most of these sediments have been assigned a Late Jurassic age although Middle Jurassic (Bajocian) ammonites and bivalves have been described from eastern Ellsworth Land. Provenance studies suggest that the active magmatic arc was the primary source of sediment, with significant amounts of metamorphic material which may represent erosion of arc basement. At this time much of the northern end of the peninsula was blanketed by deep-sea radiolarian rich muds that formed part of a huge anoxic basin within the proto-South Atlantic region.

The Larsen Basin sedimentary succession is best exposed in the James Ross Island area. It is approximately 5–6 km thick, of Barremian to Oligocene in age and is thought to overlie radiolarian rich mudstones and tuffs of the Nordenskjold Formation. The basin fill forms a retrogressive megasequence that has been divided into three groups, the basal deep marine Gustav Group and the overlying shallow marine to deltaic Marambio and Seymour Island groups.

Late Jurassic fossils common to all of the foregoing regions include ammonites, various representatives of the belemnite family Belemnopseidae, and Bivalves. The Bivalves include genera that are apparently unique to the southern high latitudes and others which form striking cosmopolitan and bipolar distributions. It is possible to trace the Antarctic marine fossil record into the early Cretaceous period using strata exposed in the sedimentary basins flanking both sides of the Antarctic Peninsula, which in some cases include prolific faunas of bivalves, gastropods, and brachiopods. The same localities have also yielded a diversity of plant macrofossils and microfossils. Collectively these suggest that throughout the Late Jurassic to Early Cretaceous much of the Antarctic continent was covered by open-canopied rainforests comprising podocarp and araucarian conifers, associated with ginkgoes, and an understory of ferns, lycopods, and bryophytes. Cool temperate moist climates prevailed in Antarctica throughout the Early Cretaceous.

In mid-Cretaceous times, the sedimentary infill of the Latady basin and associated volcanic rocks were folded and overthrust during a deformation event generally referred to as the Palmer Land event. Folding is on a kilometer scale with variable fold geometries. Folds are open to isoclinal, upright to recumbent, symmetric to asymmetric, and angular to chevron in profile. A penetrative, axial planar cleavage is well developed in finer grained rocks. Overthrust sense and fold vergence is to the east and southeast, and fold axes and faults strike parallel to the curvilinear long axis of the Antarctic Peninsula.

On James Ross Island in the back arc region the near complete sequence of fossiliferous Late Cretaceous sedimentary rocks is one of the most important in the southern Hemisphere. It contains, amongst other things, a distinctive high-latitude fauna of Cretaceous terrestrial vertebrates that includes small hypsilophodontid dinosaurs and therapods such as *Allosaurus* and a probable labyrinthodont. By the end of the Cretaceous, a podocarp-*Nothofagus* rainforest covered much of the area, extending into the Palaeocene to Eocene. It grew under cool-temperate highly seasonal climates with a substantial cooling at the end of the Cretaceous period.

Seymour Island, also within the Larsen Basin, has been referred to as the Rosetta Stone of Antarctic palaeontology, yielding prolific invertebrate and vertebrate faunas. The middle to late Eocene La Meseta Formation is the principal fossiliferous unit providing invertebrate bivalves, gastropods, echinoderms, decapod crustaceans, and brachiopods, and vertebrate sharks, teleost fish, turtles, plesiosaurs, birds (including giant penguins), marine mammals (including whales), and primitive marsupials. The formation shows the first compositional elements of the modern marine fauna.

Isolation of Antarctica

Drake Passage opened 35 Ma and the Antarctic Peninsula ceased to be attached to Southern South America following sea floor spreading in the Scotia Sea. This had a profound affect on Antarctica leading to the development of the circumpolar current, climatic cooling, and the development of permanent ice sheets on Antarctica from approximately 15 Ma. From 23 Ma onwards the sedimentary record is largely one of glaciogenic strata in which the recovery of both macrofossils and microfossils is usually poor.

Subduction also progressively ceased during this time period along the western sea board of Graham Land following a series of ridge crest–trench collisions. Postsubduction alkali magmatism occurred in a few scattered localities along the length of the peninsula. On Alexander Island, basanites, tephrites, alkali, and olivine basalts ranging in age from 15 to less than 1 Ma were erupted on to the Mesozoic accretionary complex. At Seal Nunataks on the eastern side of the peninsula, alkali and olivine and minor tholeiitic basalt occur to the east of the calc alkaline batholith and overlie the back arc sedimentary succession on James Ross Island. Subduction continues to the present day where the remnant Drake Plate is subducting beneath the northern tip of the Antarctic Peninsula.

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See also **Antarctic Peninsula; Antarctic Peninsula, Glaciology of; Bransfield Strait and South Shetland Islands, Geology of; British Graham Land Expedition (1934–1937); Drake Passage, Opening of; Fossils, Invertebrate; Fossils, Plant; Fossils, Vertebrate; Geological Evolution and Structure of Antarctica; Gondwana; Islands of the Scotia Ridge, Geology of; Palmer, Nathaniel; Plate Tectonics; South Shetland Islands**

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ANTARCTIC PENINSULA, GLACIOLOGY OF

In a glacial regime, falling snow accumulates and is compacted into ice that flows under its own weight, ultimately to melt or calve as icebergs into the sea. The regime of the Antarctic Peninsula's plateau ice caps, many mountain glaciers, and ice shelves is quite different from that of the flatter, drier, and colder East and West Antarctic ice sheets. Protruding north into the path of the circumpolar westerly airflow and the marine Circumpolar Deep Water current, the climate of this long, sinuous mountain chain is markedly more maritime than polar continental. Relatively mild but stormy weather deposits an average 0.87 m of water-equivalent precipitation annually compared with the continental average of 0.14 m, with up to 10 m of snow falling each year on the high central plateau. Although covering only 3% of the Antarctic continent, the peninsula receives 18% of its snowfall and this maritime climate and high relief give the region a dynamic and diverse glacial regime, one that is currently experiencing rapid change.

Snow falling on the Antarctic Peninsula is drained by over 400 glaciers flowing either west into the Bellingshausen Sea or east into the Weddell Sea. The largely unvisited western glaciers from 63° to 70° S are mostly short, steep, and heavily crevassed. They flow rapidly at up to 6 m per day down deeply incised fjords through the coastal mountain chain before calving into the many ice-clogged bays along this stretch of coast. Further south, in Palmer Land, the plateau broadens and the westward slope is gentler. The glaciers here form a near-continuous ice cover flowing relatively slowly into George VI ice shelf. This cover, the thickest on the peninsula at over 1000 m, is pierced only by isolated mountain peaks.

Although the peninsula's cordillera spine is just 100 to 200 km wide for most of its length, a sharp climatic contrast exists between the east and west coasts. The eastern flank receives cold southerly winds and is protected from the relative warmth of the Circumpolar Deep Water current. Mean annual temperatures are –5°C to –17°C, typically 3°C–5°C lower than the west. In these colder conditions, ice shelves historically have fringed almost all of the peninsula's east coast. These shelves, floating slabs of ice up to 200 m thick, extending up to 200 km offshore and ending in a 1000 km long vertical ice cliff, are supplied by the influx of ice from the glaciers draining east from the plateau drainage divide and by new snowfall onto the shelf. This is balanced by ice loss through iceberg calving, basal melt, and, in the north, surface melting when temperatures rise above freezing in summer.

Today, the Antarctic Peninsula glacial regime continues to adjust to changes in climate, ocean circulation, and sea level over a range of time scales but data on its history are limited. At the height of the last ice age in this region, approximately 35,000 years ago, an ice sheet several hundred meters thicker than present extended 100–200 km out onto the continental shelf to the east and west, drained by large ice streams that created the ice-sculpted form of the current sea bed revealed by recent bathymetric mapping. From 17,000 to 10,000 years ago the peninsula ice sheet thinned and retreated. This is thought to have been driven by a sea level rise of around 100 m brought on by melting of the Northern Hemisphere ice sheets, a rise that would have floated the grounded margins of the peninsula ice. By around 9,500–6,000 years ago, relatively mild and humid conditions were established. Grounded ice cover had retreated to near the present coastline, and the bare rock we see today in some coastal areas was exposed and began to be colonized by penguins, whose relict rookeries can be radiocarbon dated. There followed a partial readvance of glaciers and ice shelves succeeded by the mildest, most humid conditions of the Holocene, the climatic optimum, 3,000 years ago. Another flip back to distinct and rapid cooling culminated in the Little Ice Age glacial advance in the eighteenth and nineteenth centuries CE. The strength of the dominant high-pressure atmospheric system that sits over Antarctica is believed to have been a key control of the region's climate throughout this period.

Over the last century, the Antarctic Peninsula climate has veered into a period of rapid and significant warming. Instrumental measurements since the 1950s show an increase in mean annual temperature of around 2.5°C, four times the global mean. With summer temperatures already around freezing, melting intensity (the number of positive degree–days) has increased by up to 74%. Concurrently, 87% of glacier fronts retreated in a wave of change spreading from north to south. Most notably, seven ice shelves closest to the southward-migrating limit of ice shelf viability, defined by the January 0°C isotherm, have retreated substantially with four disintegrating: a loss of nearly 20,000 km^2. Several had previously disappeared and reformed as the Holocene climate oscillated; however, the latest to collapse, the 11,500 km^2 Larsen B, had existed continuously since its formation 10,500 years ago when the grounded ice sheet receded from the continental shelf. This suggests that the current conditions are unprecedented since before the last ice age, at least 110,000 years ago. Research into the changes on the peninsula suggests three key factors in ice shelf collapse: (1) warmer ocean waters thin and weaken the shelf; (2) a retreating front breaks through the "compressive arch" of flow that helps lock the shelf together in an embayment, allowing it to accelerate and thin further; and (3) summer melting floods crevasses in the shelf, creating a wedge more dense than the surrounding ice that drives through to the base. Weakened in this way, 3250 km^2 of the Larsen B collapsed in less than a month in summer 2002.

The loss of floating ice shelves, although dramatic, does not directly affect global sea level because they are already displacing seawater. Recent satellite observations after the Larsen A and B collapses revealed the more significant consequences of their loss: Their grounded tributary glaciers accelerated by up to eight times, causing rapid thinning as ice stored on land was discharged to the sea. The volume of ice involved and consequent sea level rise was small but this is seen as an important analogue for the much larger ice stream-ice shelf systems of the East and West Antarctic ice sheets, through which 80% of Antarctic ice drains. It is now clear that intact shelves restrict the flow of their tributary glaciers. Their loss allows the glaciers to accelerate and thin, a process that could threaten the stability of the much greater body of ice in the West Antarctic Ice Sheet. The Antarctic Peninsula's changing glacial regime is distinct in several ways from the rest of the continent, but nonetheless it serves as an important bellwether for the future evolution of the Antarctic ice sheets.

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See also **Antarctic Ice Sheet: Definitions and Description; Antarctic Peninsula; Circumpolar Deep Water; Climate; Climate Change; CryoSat; Earth System, Antarctica as Part of; Glaciers and Ice Streams; Ice Ages; Ice Sheet Mass Balance; Ice Shelves; Icebergs; ICESat; Larsen Ice Shelf; Paleoclimatology; Precipitation**

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ANTARCTIC PETREL

The Antarctic petrel *(Thalassoica antarctica)* belongs to the "fulmarine petrels," a small subfamily of tube-nosed seabirds highly adapted to life in cold polar oceans. The other fulmarines are snow petrel, Cape petrel, the two species of giant petrels, and the southern and northern fulmar. Only the last species has found its way into the Arctic; all others roam the Southern Ocean and breed on the Antarctic continent and sub-Antarctic islands. The Antarctic petrel has a distinctive dark brown-and-white plumage, with a broad white bar over the dark upper wing and tail (where Cape petrels are irregularly spotted) and with white underparts.

In its choice of breeding locations, the Antarctic petrel is the most extreme polar bird on Earth, and because of that still a bit of a mystery bird. Breeding is known only from continental east Antarctica with several colonies on coastal islands and rocky outcrops. But the main concentrations are found on inland nunataks, the exposed mountain peaks protruding from the Antarctic icecap. In late summer at the maximum retreat of sea ice, nunatak colonies may be several hundreds of kilometres away from nearest open water.

The largest known Antarctic petrel colony is on the Svarthamaren Mountains in Dronning Maud Land, with 250,000 breeding pairs and a total of about 820,000 individuals including nonbreeders. Overall, as of 2005, we know about thirty-five Antarctic petrel colonies with a documented total of half a million breeding pairs. However, an estimate derived from at-sea studies in three of four apparent centres of oceanic occurrence around Antarctica suggests a population as high as 4–7 million breeding pairs (10–20 million individuals). In spite of the tentative nature of such an estimate, the disparity with the colony-derived figure suggests potential existence of large, as yet undiscovered colonies. Such colonies may particularly exist in the inland parts of western Antarctica and Victoria Land, where a complete mismatch exists between known colonies and bird numbers at sea. Antarctic petrels nest fully in the open in large tightly packed colonies on exposed boulder slopes, but nevertheless the vast interior of the Antarctic continent can still hold mysteries.

At sea, Antarctic petrels prefer the subzero temperature waters within and just north of the marginal ice zone. Here they are seen in fast flying flocks or in large concentrations roosting on icebergs. During winter, they remain in this narrow latitudinal band around the sea ice. They seem not to visit the breeding colonies over winter, nor do they migrate farther north. Already in sub-Antarctic waters, the species is an unusual observation, and unfortunate stragglers that end up near the Southern Hemisphere continents are a rarity.

Breeding is highly synchronized among Antarctic petrels even between the coastal and inland colonies. In spring (late September to early October), Antarctic petrels aggregate near the ice edge and then depart south for their prebreeding visit to the colony. At this time of year, the combined flight distance over sea ice and ice cap to the colony may exceed 2000 km of flight one way. With such flight capacities, birds from deep inland colonies may be able to cross the Antarctic Peninsula. Quite a challenge for a typical seabird! But radar echo images from Halley Station suggest that in spring, Antarctic petrels may be commuting between their inland colonies and open water at altitudes of 1000 m.

After this long flight, Antarctic petrels show up at the colonies in the second week of October. For about two weeks they remain there to reestablish partner bonds and nest ownership, clearing away snow, engaging in courtship and copulating. Towards the end of October, all birds depart for the long return flight to open water to replenish their energy reserves. The colonies are totally deserted during this "prelaying exodus."

But within 3 weeks all of them return. The females immediately lay the single egg that can not be replaced if lost. The nest is not more than some rock fragments and dirt scraped together. Virtually all laying is synchronized between 20 and 30 November. Females leave the males behind for the first long incubation shift, which may last up to two weeks. The whole incubation takes almost seven weeks in which males and females alternate incubation duties in gradually shortening shifts. Chicks hatch in the second week of January, after which it takes another seven weeks before they are ready to fledge in late February to early March. Parents guard the chick for the first 10–15 days. During this time, failed and nonbreeders also still attend their nest sites, but towards the end of January all adults leave and only successful breeders pay short visits to feed the chicks. After the colony period, adults return to sea to moult their plumage. Some birds may make short colony visits in late April to early May, but most probably stay out at sea until the next spring.

Under the extreme Antarctic conditions, where Antarctic Petrels breed earlier than the other petrels, breeding success is often low, and typically well under 50% of initial attempts. But the adults are long-lived (over 97% adult annual survival), so frequent breeding failure can be compensated by high life expectancies.

As far as is presently known, Antarctic Petrel populations are currently stable. But on a local scale, serious effects of climate change have been observed. Increased snowfall in Wilkes Land not only caused increased egg freezing but made colonies accessible to predatory southern giant petrels *(Macronectes giganteus)*. Predation strongly reduced breeder survival and indirectly caused near total breeding failure as temporarily abandoned eggs were taken by South Polar skuas *(Catharacta maccormicki)*.

The diet of Antarctic petrels is dominated by fish, mainly Antarctic silverfish and lanternfishes. Squids are also a common prey for self-provisioning birds. Crustaceans such as krill and amphipods are an extremely common diet item but only occasionally dominate other prey in diet mass. Opportunistic feeding may include jelly-type prey. This diet of Antarctic petrels should not lead to a lack of concern about potential competition with commercial krill harvesting. Indirectly, compared with direct krill consumption, their diet may put heavier demand on krill stocks because the fish and squid themselves may depend on krill.

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See also **Antarctic: Definitions and Boundaries; Cape Petrel; Northern Giant Petrel; Seabird Conservation; Seabird Population and Trends; Seabirds at Sea; Snow Petrel; South Polar Skua; Southern Giant Petrel; Squid; Zooplankton and Krill**

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ANTARCTIC PRION

The Antarctic prion (*Pachyptila desolata* Gmelin 1789) is a member of the order Procellariiformes or tube-nosed seabirds—the petrels, albatrosses, and shearwaters. *P. desolata* is one of the most ubiquitous petrels of the Southern Ocean. These birds can often be seen flying in large, erratic swarms resembling flocks of pigeons or doves in flight over the ocean. Perhaps it is this image that suggests their other common names—dove prion, dove petrel, and whalebird.

Antarctic prions belong to the genus Pachyptila (*pachy,* broad; *ptila,* wing), the taxonomy of which is still debated. *P. desolata* are midsize petrels, weighing between 150 and 160 g with a wingspan of about 65 cm. At sea, these birds can be seen individually, in small groups, or in flocks of several thousand birds. Like other prions, *P. desolata* is a cloudy, blue-gray color, with a dark "M" mark across the backs of the wings. The blue-gray on top is contrasted by a white belly and under parts. The forehead, crown, and nape of the neck are also blue-gray color, with a grayish-black suborbital patch on each side of the head. This coloration allows them to blend into the backdrop of the ocean when they are viewed from above or to the side. Procellariiform aficionados are fond of noting that prions are so effective at camouflage that navy ships even co-opted their blue-gray color, presumably to reduce their visibility to the enemy.

Antarctic prions were also colloquially known as "scoopers" by whalers because of their unique style of foraging. These birds capture their prey by hydroplaning over the surface of the ocean with their wings extended and their heads submerged. At the same time, the bill is open exposing an upper mandible with a set of fringed strainers that are reminiscent of a whale's baleen. As the bird flies, water and crustaceans are flushed through the strainers, assisted by the tongue and other muscular movements of the bill, while, in the meantime, the skin of the bottom mandible extends into a pouch to hold the prey items. Thus, by skimming along the surface of the water, the bird is able to filter fine crustaceans and other zooplankton from the ocean's surface without ever seeing them at all. Antarctic prions are versatile in their foraging habits. In addition to filter feeding, they can also dive to at least 3 m and are capable of hunting prey by snatching it with their bill. In addition, detailed sensory studies have shown that Antarctic prions have reduced binocular vision compared with other petrels, suggesting that visually pinpointing and grasping prey may not be as essential to their daily routine as it might be for other tube-nosed species. These birds also have a remarkable sense of smell that allows them both to track their prey by smell like a bloodhound and to detect productive areas of ocean where prey aggregations are likely to be found. Results from numerous experiments suggest that olfaction is critical to their ability to find their prey, which includes a variety of crustaceans, mesopelagic fish, and squid.

Antarctic prions have a near-circumpolar distribution and are currently not globally endangered. These birds are currently found nesting on a number of sub-Antarctic islands including South Georgia, the South Sandwich Islands, the South Orkney Islands, the South Shetland Islands, Îles Crozet, Îles Kerguelen, Heard Island, Macquarie Island, the Auckland Islands, and Scott Island. These birds breed in a more southerly range than other prion species, and historically have nested even on the Antarctic continent. *P. desolata* nests underground, either in burrows or in rocky crevices that can be up to 1 m deep. Birds tend to nest together in loosely aggregated or dense colonies, depending on the habitat and location. Antarctic prions are subject to predation by other birds, including South Polar skuas *(Catharacta maccormicki)*. This threat restricts them to a nocturnal lifestyle on land. Prions, in general, are also particularly vulnerable to rats (*Rattus* spp.) and feral cats *(Felis catus),* which can decimate populations in breeding colonies.

As with other procellariiforms, Antarctic prions are long lived and assumed to be monogamous because they return to the same burrow year after year to rear their offspring. The breeding season lasts throughout the summer months from late September through March or early April, depending on the location. Birds nest annually and rear a single offspring. Pairs come back to the nesting colony in spring, mate, and then go back out to sea for a "honeymoon" period (also known as the pre-egg exodus) while the egg develops. This might be a period in which the couple explores nearby foraging location, but its purpose is still open for speculation. Once the egg is laid, it must be incubated for at least 42 days, but eggs can also tolerate considerable neglect if foraging conditions are not good for the parents. In such cases, incubation can last as long as 50 days. Antarctic prions can recognize the scent of their burrow, and use olfaction to locate it within the colony. Recent studies have also shown that these birds are sensitive to individual-specific odors, and may even use odor cues to recognize the scent of their mate. Prions are also noisy in breeding colonies and pairs can frequently be heard vocalizing to each other in the burrow during incubation shift changeovers.

The way in which Antarctic prions provision chicks has been studied in detail at Îles Kerguelen and at South Georgia. At Kerguelen, researchers have shown that Antarctic prions provision chicks using a dual foraging strategy. Here, parents alternate long foraging trips of about a week with a cluster of shorter trips of 1–2 days. The long foraging trips allow parents to feed themselves while the short foraging trip allows them to collect food for the chick. Food for the chick is regurgitated as concentrated stomach oil, which is the primary way nearly all procellariiforms feed their young. Although they are fed daily, the growth rate of the chicks depends on the quality of the food available. Thus, if krill (*Euphausia* spp.) is farther offshore, chicks may grow more slowly than when krill is readily at hand. Meanwhile, at South Georgia, researchers have shown that Antarctic prions can successfully rear young even in low quality years when other procellariiforms fail. This is because, unlike many other species, Antarctic prions have the ability to switch among available food resources, possibly due to the fact that they can resort to filter feeding on calanoid copepods close to shore during time when a high-quality food resource like Antarctic krill is not available.

Chicks fledge at about 45 days and adults leave the colony by late summer, typically at least a week before their young have fledged. Because Antarctic prions are too small to carry satellite transmitters, little is currently known about their behavior once they leave the nest.

GABRIELLE NEVITT

See also **Auckland Islands; Birds: Diving Physiology; Crozet Islands (Îles Crozet); Fish: Overview; Heard Island and McDonald Islands; Kerguelen Islands (Îles Kerguelen); Macquarie Island; Petrels: Pterodroma and Procellaria; South Georgia; South Orkney Islands; South Polar Skua; South Sandwich Islands; South Shetland Islands; Squid; Zooplankton and Krill**

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ANTARCTIC SURFACE WATER

In the Southern Ocean, the strong eastward flow of the Antarctic Circumpolar Current is characterized by continuous fronts that circle the globe. These fronts are readily distinguishable by the isopleths of properties sloping upward to the south. The fronts are manifested at the surface as strong horizontal gradients in temperature, salinity, and other oceanic properties over distances of $\sim$10 km. These property gradients form boundaries between water masses, separating the relatively warmer sub-Antarctic surface waters of the north from the colder Antarctic Surface Water to the south.

World ocean water masses are typically identified by distinctive signatures of temperature, salinity, dissolved oxygen, and nutrients. Drake Passage is the narrowest passageway through which the Antarctic Circumpolar Current must squeeze and therefore provides a convenient chokepoint where Southern Ocean water masses and their variations can be readily measured and studied. The temperature and salinity data collected in Drake Passage represent one of the longest, year-round time series for examining property characteristics and variability in the upper waters of the Southern Ocean. At other longitudes there are likely to be small variations in the horizontal property distribution of the upper ocean water masses, as the Antarctic Circumpolar Current meanders north and south in response to changes in bottom topography. In Drake Passage the main fronts of the current are distinct features that divide zones of uniform water properties, while in other regions the fronts may split or merge to reveal a more complex, filamented structure.

Property Characteristics of Upper Ocean Water Masses in the Southern Ocean

Between 58° S and the continental margin of Antarctica at 62° S, the Antarctic Surface Water (AASW) is defined by surface waters with subzero temperatures and salinities fresher than 34 above 150 m. During the Southern Hemisphere winter, the AASW is colder, slightly more saline, and extends to the sea surface, where temperatures can reach as low as –1.9°C, near the freezing point of water at these salinities. Surface heating and ice melt during the spring and summer months warms and freshens the AASW in the upper 50 m. A remnant of the deep winter mixed layer persists throughout the austral summer and is generally marked by a subsurface temperature minimum, typically below 0°C and centered around 100 m. This cold subsurface layer is often referred to as Winter Water (WW). The large temperature change at the northern extent of the WW marks the position of the Polar Front, one of the major circumpolar fronts associated with strong flows in the Antarctic Circumpolar Current. The Polar Front is dynamically determined as the region where cold AASW sinks beneath the warmer sub-Antarctic surface waters to the north, and can be defined as the northern extent of waters colder than 2°C at 200 m. The Polar Front can appear in satellite observations as a strong gradient in sea surface temperature (SST), particularly in winter months when the 2°C isotherm outcrops into the surface layer. Summer heating of the surface layer results in a more southerly position than that determined from subsurface temperature measurements. In Drake Passage the mean Polar Front location is at 58.3° S in both seasons, but its location is more variable during winter. Although Polar Front meanders at other longitudes result in more seasonal variability, the dynamic expression of the Polar Front still separates the Antarctic and sub-Antarctic surface water masses.

Below the AASW lies the relatively warmer and more saline Upper Circumpolar Deep Water mass (UCDW), which has a temperature maximum near 2°C at 300 m. UCDW displays the least temporal and spatial variability in temperature of all upper ocean water masses in the Southern Ocean. In contrast, salinity increases from 34.0 at the base of the AASW to 34.7 at 600–700 m at the top of the underlying Lower Circumpolar Deep Water (LCDW). Salinity controls the density, and thus the stability, of the water column at these latitudes. The UCDW is largely a product of mixing between deep waters formed in the North Atlantic and in the western Indian and eastern Pacific sectors of the Southern Ocean, which gives it low oxygen and high nutrient concentrations. The UCDW and LCDW shoal poleward beneath the sea surface, providing a marker for the southern extent of the Antarctic Circumpolar Current.

The relatively fresh surface water in northern Drake Passage is Subantarctic Surface Water (SASW), which is also warmed by heating at the surface during summer. Its surface temperature and salinity ranges (4°C–14°C; 33.5–34.0) are larger than in AASW due to greater variations in solar heating, precipitation and evaporation at lower latitudes. Below the surface layer lies the Subantarctic Mode Water (SAMW), characterized by low variability in temperature and salinity from 300 to 700 m. SAMW temperatures range from 4°C–5°C while salinities range from 34.1 to 34.2. The southern extent of the SAMW in this depth interval, the Subantarctic Front, marks the northern boundary of the Antarctic Circumpolar

Current, located near 56° S in Drake Passage. As with the Polar Front, the Subantarctic Front also meanders and can appear to be filamented with longitude around the Southern Ocean.

Between the Polar Front and the Subantarctic Front is a transitional region for Antarctic and Subantarctic surface waters. Though a southward shoaling of isotherms is characteristic, individual vertical profiles in this zone commonly show water mass interleaving and temperature inversions. Warm-core and cold-core eddies extending from the surface layer to depths below 700 m also frequently populate the region. These eddies may be an efficient mechanism for the exchange of water mass properties and biological organisms such as phytoplankton across the Antarctic Circumpolar Current.

The Role of Surface Waters in the Meridional Overturning Circulation

The strong westerly winds that encircle the globe in the vicinity of the Antarctic Circumpolar Current drive a northward flow, or Ekman transport, in the surface layers. V. W. Ekman developed a theory in 1905 showing that wind stress acting on the surface layer is affected by the Earth's rotation, such that flow is to the left of the wind in the Southern Hemisphere (and to the right in the Northern Hemisphere). As the surface waters move northward, surface temperatures increase from 1°C to 4°C–5°C, implying an oceanic heat gain south of the Polar Front. This is also a "buoyancy" gain and is thought to be achieved by north-south excursions of atmospheric and oceanic frontal storms, which provide the heat and fresh water that reduces the density of the surface waters.

South of the westerly wind stress maximum, the Ekman transport is divergent, and mass conservation requires that this northward motion be balanced by a southward flow. Evidence suggests this compensation can generally be attributed to the southward shoaling UCDW. Since Drake Passage latitudes have no topography above 2000 m to support an east-west pressure gradient to drive a southward geostrophic flow, the poleward transport and upwelling of the UCDW is probably accomplished by eddies. North of the westerly wind maximum, the Ekman transport is convergent so that the surface waters are driven down into the ocean interior. In addition, a buoyancy loss results from air-sea cooling in winter, deepening the surface layers and leading to the formation of the SAMW near the Subantarctic Front. While SAMW is generally characterized by a well-mixed layer of high oxygen content, its properties may also vary due to the north-south meandering of the Subantarctic Front. The coldest, densest SAMW is the Antarctic Intermediate Water (AAIW), which originates as a low-salinity layer formed in the region of deepest mixed layers in the South Pacific just west of Chile. Uncertainty remains about the role of the northward transport of cool, fresh surface waters in maintaining the volume and thickness of SAMW, but its distinctive low-salinity, high oxygen properties provide a clear signature that can be traced throughout the global ocean. The intermediate depth water masses that are formed from these surface waters are known to "ventilate" a substantial fraction of the world ocean volume.

The upper ocean meridional (north-south) circulation described above is historically known as the Deacon Cell, after Sir George Deacon who described it in 1937, and in more recent literature as the upper cell of the Meridional Overturning Circulation. Surface waters transported northward in the Ekman layer as part of this circulation play an important role in the exchange of heat and fresh water with the overlying atmosphere and sea ice in the Southern Ocean and beyond. Variability in atmospheric forcing and climate in this region can be directly communicated via water properties to the ocean interior and thereby influence the storage of heat and freshwater at lower latitudes. Because the solubility of carbon dioxide increases with colder water, the Antarctic surface waters and the Meridional Overturning Circulation are thought to play a key role in regulating the ocean's capacity for the uptake of this greenhouse gas. Temperature and salinity variations in Antarctic surface waters may thus have important implications for global climate change.

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See also **Antarctic Intermediate Water; Chemical Oceanography of the Southern Ocean; Circumpolar Current, Antarctic; Circumpolar Deep Water; Eddies in the Southern Ocean; Southern Ocean: Climate Change and Variability; Southern Ocean: Fronts and Frontal Zones; Southern Ocean: Vertical Structure; Thermohaline and Wind-Driven Circulations in the Southern Ocean**

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ANTARCTIC TERN

Breeding populations of this species are distributed on Tristan da Cunha, Gough Island, Bouvetøya, the Prince Edward Islands, Îles Crozet, Îles Kerguelen, Île Amsterdam, Île St. Paul, Heard Island, Macquarie Island, the Campbell Islands, Auckland Islands, Snares Islands, Antipodes Islands, Bounty Island, and offshore islands of New Zealand. In the region of the Antarctic Peninsula, breeding populations reach 68° S. They also breed on the South Shetland Islands, South Orkney Islands, South Georgia, and the South Sandwich Islands. The total population may be 50,000 breeding pairs.

Antarctic terns breed on the coasts and islands of the Antarctic and sub-Antarctic seas, especially on cliffs, rocky islets, and beaches with or without vegetation, but also on gravel beaches and moraines. In the northern area of their distribution, they breed in different places: on Tristan da Cunha they are found on ledges on offshore islands, and on the Snares and Bounty Islands they nest solitarily on cliff ledges. In many of these islands, the original breeding places have been abandoned following the introduction of predators, and the birds have moved to safer places without rats (*Rattus* spp.) or cats *(Felis catus)* (e.g., on Île Amsterdam, where they are now found on coastal cliffs inaccessible to cats).

Outside the breeding period, they have been observed to be more oceanic, occurring near ice edges in Antarctica, and also on rocky headlands and beaches in South Africa or in the area of the cold-water currents of South America. Antarctic terns are not ship-followers. There are few data on the movements of Antarctic terns, but the species is believed to be only partly migratory. In the region of the South Shetland Islands, in the maritime Antarctic, birds have been observed throughout the year. Large winter flocks roost in South Africa.

The birds return to breed in loose colonies adjacent to coastal waters, in some colonies very early (mid-September in the South Shetlands Islands). Courtship behaviours such as courtship feeding and coordinated flights occur and prospecting for nest sites has been seen in early spring. The nests are shallow scrapes in pebbles or shells. Some birds prefer slight depressions in bare rocks or a thin layer of soil or vegetation. On sub-Antarctic islands, thin layers of leaves are used for nest building. Most scrapes contain small stones. Laying occurs between mid-November and February, later in more northern areas than in the south. There are usually no more than forty widely distributed nests in any one locality. This species is assumed to be monogamous, and the pair bond may be maintained between breeding seasons. The birds defend a small area around the nest. They lay two to three mottled eggs in open, shallow, pebble- or shell-lined scrapes on the ground. Incubation begins when the first egg is laid. Incubation is by both parents for 23 days, with the chicks hatching from December to late February. The nests are difficult to see as the eggs and chicks are well camouflaged. Adult Antarctic terns cooperate to defend their colonies from predatory birds and mammals, although skuas (*Catharacta* spp.) and kelp gulls *(Larus dominicanus)* still occasionally manage to take eggs or chicks from unattended nests. Skuas are the main predators. The high rate of predation is the reason for frequent re-laying. Fledging of the chicks occurs from January through to May, 23–32 days after hatching. The parents attend their young for several weeks after fledging, occasionally feeding their chicks.

Breeding success fluctuates greatly; on King George Island, for example, it ranges between 3% and 86%. The most important factors are human disturbance, bad weather conditions (especially snow in spring), and a high predation rate, especially by skuas and, in northern areas, also by rats. Antarctic terns move their colony not only from year to year but also during the breeding season after human disturbance or predation by skuas.

Antarctic terns feed mainly on small fish like the Antarctic herring and on crustaceans such as krill, amphipods, and isopods, and sometimes on molluscs (limpets), polychaetes, algae, and insects. There are different foraging methods, the shallow plunge with full submersion or sometimes only surface plunging or dipping. This depends on the conditions at sea. If there is a calm sea, they prefer plunging to catch fish or dipping to catch crustaceans but, in a rough sea, surface plunging is the only effective means of obtaining food. They also forage inshore or in lakes.

Their social behaviour has been studied in detail on King George Island. Agonistic behaviour is the vicious defence of the nesting territory against other Antarctic terns and other species. There is a very interesting bill-down threat display with loud calls, pressing the body forward with tail up and bill pointed down. The wings are away from the body. This behaviour is also shown by the neighbours, and is repeated sometimes. A similar behaviour is the bill-up threat display against overflying birds, where the bill is pointed skyward. There are some very common forms of behaviour of varying intensities: crouching, bowing, the aggressive upright, and the bent posture for territory defence. Sometimes there are aerial fights between neighbours. When skuas intrude into a tern colony, the terns chase and mob the intruders.

Sexual behaviour includes ground courtship, courtship flights, a greeting ceremony, and courtship feeding. The courtship flights occur before egg-laying. The male arrives carrying a small fish, which is offered to the female. After the female has eaten the fish, the pair tests several nest sites by pressing their breasts into the potential scrape and scraping with the feet. During courtship feeding, the female holds her wings low and utters begging calls. During parading, the male makes small steps, with lowered wings and raised head. The greeting ceremony includes erect and bent postures, and involves lowering the wings, raising the tail and tilting the head. Copulation occurs six days before egg laying.

A chick begs by rubbing its bill against that of its parent. After this, the chick is fed by the adult, not necessarily by the parent that has come from the sea. Normally the foraging adult arrives with a fish and lands 10–20 m away from the nest. The begging chick runs out of its shelter (vegetation or stones) to the adult and is fed the fish. The chick then returns to its original place and the adult goes foraging again. Hiding in vegetation or behind stones is a very important antipredator behaviour of chicks.

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See also **Algae; Amsterdam Island (Île Amsterdam); Arctic Tern; Auckland Islands; Birds: Diving Physiology; Bouvertøya; Campbell Islands; Crozet Islands (Îles Crozet); Fish: Overview; Gough Island; Heard Island and McDonald Islands; Kelp Gull; Kerguelen Islands (Îles Kerguelen); Kerguelen Tern; King George Island; Macquarie Island; Prince Edward Islands; Skuas: Overview; South Georgia; South Orkney Islands; South Sandwich Islands; South Shetland Islands; St. Paul Island (Île St. Paul); Terns: Overview; Zooplankton and Krill**

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ANTARCTIC TREATY SYSTEM

Who governs Antarctica? That was the issue that faced twelve countries that had been active in the Antarctic during the International Geophysical Year (1957–1958). Almost 50 years on, there is still no answer to that question upon which all parties could agree other than "the Antarctic Treaty System." Practical? Yes. Legally watertight? For as long as the system exists that question does not need to be answered—it works.

The Antarctic Treaty System (ATS) is the whole complex of arrangements made for the purpose of regulating relations among states in the Antarctic. At its heart are the Antarctic Treaty itself, numerous Recommendations, Measures, Decisions, and Resolutions adopted at meetings of the Antarctic Treaty Parties, and which have become effective in accordance with the terms of the treaty, the Protocol on Environmental Protection to the Antarctic Treaty, and three separate conventions dealing with the Conservation of Antarctic Seals (London, 1972), the Conservation of Antarctic Marine Living Resources (Canberra, 1980), and the Regulation of Antarctic Mineral Resource Activities (Wellington, 1988). Although the last convention, negotiated between 1982 and 1988, was destined, in the event, not to enter into force, it marked a considerable advance in the attitude of Antarctic Treaty Parties to environmental protection. Many of the concepts featured in the Protocol on Environmental Protection were first elaborated in the mineral resources convention.

The ATS also includes the results of Meetings of Experts and the decisions of Special Consultative Meetings and, at a nongovernmental level, reflects the pervasive effects on many aspects of the system of the work of the Scientific Committee on Antarctic Research (SCAR) and, since 1989, of the Council of Managers of National Antarctic Programs (COMNAP). Measures and actions have been adopted or taken as and when a present or future need for them has been perceived. The practice has been essentially pragmatic, and it was not until the conclusion of the Protocol on Environmental Protection in 1991 that there was a systematic attempt to provide a code for the regulation of all Antarctic activities other than those covered by the two separate conventions dealing with the conservation of seals and marine living resources.

The Antarctic Treaty

The original parties to the treaty were the twelve nations that were active in the Antarctic during the International Geophysical Year of 1957–1958, and then accepted the invitation of the US government to participate in the diplomatic conference at which the treaty was negotiated in Washington in 1959. The treaty entered into force on 23 June 1961 following ratification by Argentina, Australia, Belgium, Chile, France, Japan, New Zealand, Norway, South Africa, the Soviet Union (now Russia), the United Kingdom, and the United States. These countries have the right to participate in meetings provided for in Article IX of the treaty ("Consultative Meetings") and are accordingly known as Consultative Parties. The treaty provides for accession by any state that is a member of the United Nations, and for accession by any other state by invitation of all Consultative Parties. It provides for such states as have acceded to the treaty and have demonstrated their interest in Antarctica by carrying out substantial scientific activity there to become Consultative Parties. Thirty-three states have acceded to the treaty, and of those sixteen states have become Consultative Parties by becoming active in the Antarctic (in addition to the original twelve).

Every year (before 1991 it was every 2 years) the Consultative Parties meet "for the purpose of exchanging information, consulting together on matters of common interest pertaining to Antarctica, and formulating and considering and recommending to their Governments measures in furtherance of the principles and objectives of the Treaty." Since 1983, those countries party to the treaty that are not Consultative Parties have been invited to take part in these meetings as observers. In addition, special Consultative Meetings are convened as deemed appropriate by the Consultative Parties. Those convened to acknowledge the Consultative Party status of countries that have acceded to the treaty and have demonstrated their interest by carrying out substantial scientific activity in the Antarctic have not been attended by non-Consultative Parties. The non-Consultative Parties were invited to take part in the IVth and XIth Special Consultative Meetings, respectively on Antarctic minerals and environmental protection, as observers. Finally there have been four meetings of experts to consider questions of Antarctic telecommunications, one to consider questions of air safety, one to consider issues relating to environmental monitoring, one to consider shipping guidelines, and one on tourism and nongovernmental activities.

The Purpose of the Antarctic Treaty

The primary purpose of the Antarctic Treaty is to ensure "in the interests of all mankind that Antarctica shall continue forever to be used exclusively for peaceful purposes and shall not become the scene or object of international discord." To this end it prohibits "any measures of a military nature" but does "not prevent the use of military personnel or equipment for scientific research or for any other peaceful purpose." The treaty provides for "freedom of scientific investigation in Antarctica, promote[s] international co-operation in scientific investigation in Antarctica," encourages "the establishment of cooperative working relations with those Specialized Agencies of the United Nations and other international organizations having a scientific or technical interest in Antarctica," prohibits "any nuclear explosions in Antarctica and the disposal there of radioactive waste material" and provides for detailed exchanges of information. "To promote the objectives and ensure the observance of the provisions of the...Treaty," Consultative Parties "have the right to designate observers to carry out any inspection of...all areas of Antarctica, including all stations, installations and equipment, and all ships and aircraft at points of discharging or embarking cargoes or personnel in Antarctica."

The treaty applies to the area south of 60° S, including all ice shelves, but nothing in the treaty "shall prejudice or in any way affect the rights, or the exercise of the rights, of any State under international law...with regard to the high seas within that area." The broad practical effect of this article has been that whereas the Consultative Parties have proceeded by means of measures provided for under Article IX when dealing with matters pertaining to land and ice shelves in Antarctica, they have proceeded by means of separate conventions, with independent ratification and accession procedures, when dealing with matters that affect their rights or the exercise of their rights with regard to the seas within the area of application of the treaty—hence the conventions on the conservation of seals and marine living resources.

The Sovereignty Question

At the root of the Antarctic Treaty lies its fourth article dealing with territorial sovereignty. It safeguards the positions of three groups of states which are parties to the treaty: those that had "previously asserted rights of or claims to territorial sovereignty in Antarctica" (Argentina, Australia, Chile, France, New Zealand, Norway, and the United Kingdom), those that consider themselves as having "a basis of claim to territorial sovereignty in Antarctica" (Russia [then the Soviet Union] and the United States), and those that do not recognize "any other State's right of or claim or basis of claim to territorial sovereignty in Antarctica." The same article, however, goes on to provide that "no acts or activities taking place while the present Treaty is in force shall constitute a basis for asserting, supporting or denying a claim to territorial sovereignty in Antarctica or create any rights of sovereignty in Antarctica. No new claim, or enlargement of an existing claim, to territorial sovereignty in Antarctica shall be asserted while the present Treaty is in force." It is this "no prejudice" that has underlain the development of the Antarctic Treaty System over the years.

The safeguards of Article IV are not, however, limitless. They might not, for example, protect a state from consequences of acting in a manner that was contrary to its known position on the sovereignty issue. Some parties have attempted to proceed on an assumption that Article IV had somehow "solved" the sovereignty issue. But they, along with all other Consultative Parties, have had to recognize that if they push their view on sovereignty, whether for or against, to what would in their view be a logical conclusion, Article IV would not be able to take the strain. Following recent extensions and definitions of coastal state jurisdiction in accordance with international law, it was recognized that events (e.g., unregulated fishing or prospecting for minerals) could give rise to such strains. Consultative Parties that assert territorial claims would not accept that others should take their fish or minerals without their leave. Neither would those Consultative Parties that do not recognize territorial claims accept that their access to fish or minerals in the Antarctic Treaty Area could be denied on the basis of territorial sovereignty and coastal state jurisdiction.

Recognition of the potential for dispute inherent in these issues of economic exploitation, from which, once embarked upon, there could be no retreat by either side, gave birth, as an exercise in preventative foresight, to the living resources convention and then to the minerals convention. In the negotiation of both conventions the two sides of the sovereignty argument fought vigorously for their respective positions. The resulting conventions are expressions, on the one hand, of the strength of national interest and, on the other hand, the accommodations that could be accepted by both sides within the safeguards provided for in Article IV. It is thus that qualities of foresight in dealing with issues before they become insoluble, restraint in the pursuit of national interest, and recognition of the national interests of others, have come to mark the ATS.

The Protocol on Environmental Protection to the Antarctic Treaty

The publication in 1987 of the discovery of the "ozone hole" over Antarctica first demonstrated that humankind really was capable of changing the environment on the global scale. It acted as a catalyst for three major Antarctic events: the demise of the minerals convention four years later, the conclusion in 1991 of the Protocol on Environmental Protection to the Antarctic Treaty, and the frustration of an attempt within the United Nations to overturn the Antarctic Treaty. The protection of the Antarctic environment became the international political imperative.

The Convention on the Regulation of Antarctic Mineral Resource Activities, concluded in 1988 in Wellington following 6 years of innovative negotiation, was replaced by a ban on all mineral resource activities (except scientific research) under the terms of Article 7 of the protocol. But the scope of the protocol is a great deal wider than was recognised by those who saw in it only the minerals ban. Its objective is to ensure that "the protection of the Antarctic environment and dependent and associated ecosystems...shall be fundamental considerations in the planning and conduct of all activities in the Antarctic Treaty Area."

The environmental protection protocol establishes certain environmental principles; says that nothing in the protocol "shall derogate from the rights and obligations of Parties to the protocol under other international instruments in force within the Antarctic Treaty system"; provides that environmental impact assessment shall be the primary mechanism to ensure that the environmental principles are adhered to; establishes a Committee for Environmental Protection, full membership of which is not restricted to Consultative Parties; provides for annexes on any matter to do with the protection of the Antarctic environment to be added to the protocol; and establishes a procedure for the compulsory settlement of disputes, arising from the interpretation or application of the protocol. So far there have been five annexes to the protocol, dealing with environmental impact assessment (I), conservation of fauna and flora (II), waste disposal and management on land (III), prevention of pollution at sea (IV), and area protection and management (V). The primary purpose of distinguishing between the protocol itself and annexed measures is to provide for "amendments and modifications [of an annex] to become effective on an accelerated basis."

Scientific Committee on Antarctic Research

As befits developments under a treaty dealing with a part of the world about which comparatively little is known, and of which one of the main purposes is to establish and maintain freedom of scientific research, there is a close relationship between science and the consultative machinery of the treaty established under Article IX. Frequently a problem may be identified about which scientific advice is needed before deciding what, if any, action is required. The channel for requesting such advice is through the respective governments of the Consultative Parties to their National Antarctic Committees normally established under the auspices of their national Academy of Science or National Research Council. These National Antarctic Committees will, in turn, through their delegates submit the request for advice to the Scientific Committee on Antarctic Research (SCAR) established by the International Council for Science (ICSU).

The primary purpose of SCAR is to formulate and coordinate Antarctic scientific research programmes. The Consultative Parties have frequently needed scientific advice on a matter in hand but for the first 30 years there were no formal links between SCAR and the treaty system: the necessary channels were through national committees. A request for scientific advice would emanate from a treaty meeting, it would be referred to one of the SCAR Working Groups (now known as Standing Scientific Groups), and the advice would then be transmitted back through national committees and treaty governments to a Consultative Meeting for consideration. The advantage of these arrangements was that it distanced the science from the politics, ensuring a fair degree of independence. But things changed with the adoption of the Protocol on Environmental Protection. Its Committee on Environmental Protection implied "hands on" use of science in pursuit of environmental objectives. Thus the protocol provides for the president of SCAR to participate in the Committee on Environmental Protection, and SCAR has established a Standing Committee for the Antarctic Treaty System. There is little else in the way of formal relationship between the treaty governments on the one hand and SCAR on the other. But the system allows for the treaty governments to have access to a wide spectrum of independent scientific advice available through the scientific unions and committees of ICSU. From time to time the scientists in SCAR may, on their own initiative, seek to advise treaty governments of some concern that they feel should be taken up intergovernmentally within the consultative machinery of the treaty.

Council of Managers of National Antarctic Programmes

In the early days of the treaty there were concerns about the practical way of doing things in the Antarctic—how to design weatherproof buildings or how to get a tractor out of a crevasse. Meetings were held under the auspices of SCAR. Proven techniques could be adopted more widely; dead ends could be avoided. These meetings developed into the SCAR Working Group on Logistics. In 1989, a Council of Managers of National Antarctic Programs (COMNAP) was established to provide a freestanding forum for consultation and cooperation between countries active in Antarctica at the practical level. It has a Standing Committee on Antarctic Logistics and Operations to provide practical and technical advice. COMNAP is now less concerned with practical allowances/prohibitions and more with the nuts and bolts of cooperation on the ground so that the best use is made of costly Antarctic logistics.

International Organisations

The Consultative Parties, as and when the need has arisen, have involved other international organizations in the work of the Antarctic Treaty System. The World Meteorological Organization and the International Telecommunications Union have had representatives at specialist meetings on Antarctic meteorological telecommunications; the Food and Agriculture Organization, the International Whaling Commission, the Intergovernmental Oceanographic Commission, the International Union for the Conservation of Nature and Natural Resources (IUCN, now known as the World Conservation Union but, like ICSU, has maintained its previous acronym) are among the international organizations participating in the work of the Commission established by the Convention on the Conservation of Antarctic Marine Living Resources. Since the XVth Antarctic Treaty Consultative Meeting nine intergovernmental organizations (IOC, ICAO, IHO, IMO, IUCN, UNEP, WMO, WTO, IPCC, and PATA) have been invited to participate in the work of Consultative Meetings relevant to their respective interests. In addition, two umbrella nongovernmental organisations, the Antarctic and Southern Ocean Coalition (ASOC) and the International Association of Antarctic Tour Operators (IAATO), participate in Consultative Meetings as experts.

Has It Worked?

When the treaty was negotiated at the height of the Cold War no one knew whether the then-superpowers would be able to cooperate in the interests of maintaining the peace in the Antarctic, or whether agreement between states claiming sovereignty and those that did not recognise such territorial claims would be possible. Some said that competition for Antarctic resources would wreck the treaty. The treaty's genius was that it said only what it had to be said to provide a framework within which peace could be maintained and no more, but how it was to be maintained was left to the parties. Some thought that it should be put on the shelf until such time as a problem arose; others recognised that unless the consultative machinery was exercised it might not stand the strain when the need came. Cooperation needed to become the habit rather than the exception. Much of what the treaty has achieved over the years has been about the encouragement of that habit. The Antarctic Treaty System will continue for as long as governments maintain their interest in the Antarctic. The risk otherwise is that the treaty area might become the "scene or object of international discord"—surely unthinkable.

An afterthought: As a consequence of the provision in the Moon and Celestial Bodies Treaty of an article derived from Article IV of the Antarctic Treaty, the only part of the universe where humankind can exercise exclusive jurisdiction on the basis of territorial sovereignty is that part of planet Earth outside the Antarctic Treaty area—no shots have been fired inside the Antarctic Treaty area. For almost fifty years the Antarctic has been a political laboratory where the respective merits of jurisdiction based on territory and on nationality have been fought out in debate marked by forbearance—a tribute to those who engaged in the debates but, more than anything, to the unique and all-pervading nature and force of the Antarctic itself.

JOHN HEAP

See also **Antarctic and Southern Ocean Coalition (ASOC); Antarctic: Definitions and Boundaries; Conservation of Antarctic Fauna and Flora: Agreed Measures; Convention on the Conservation of Antarctic Seals (CCAS); Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Convention on the Regulation of Antarctic Mineral Resource Activities (CRAMRA); Council of Managers of National Antarctic Programs (COMNAP); Geopolitics of the Antarctic; International Geophysical Year; Ozone and the Polar Stratosphere; Protocol on Environmental Protection to the Antarctic Treaty; Scientific Committee on Antarctic Research (SCAR); United Nations; United Nations Environment Program (UNEP); World Conservation Union (IUCN); World Meteorological Organization**

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ARCHAEOLOGY, HISTORIC

Historical archaeology in Antarctica and on the continental and sub-Antarctic islands has been mostly limited to site surveying to provide basic documentation of historic sites, the removal of ice within historic huts, and a few excavations.

There are a wide variety of sites of interest to historians and archeologists associated with early sealing and whaling, farming activity, science, shipping, and exploration. Most are located in coastal areas where there was ready access from the sea and are generally of great archaeological significance.

For Antarctica and the continental islands the sites include:

- Evidence of British and American sealers and whalers, dating back to the late 1700s with remains of ships; rock and wood huts and occupied caves found in the South Shetland Islands off the Antarctic Peninsula.
- Industrial sites associated with whaling on the island of South Georgia and Deception Island.
- Wooden and rock huts, caves, camp sites, middens, supply depots, message posts, cairns, memorial crosses, and graves associated with the "Heroic Era" of exploration (1895–1917) in the Ross Sea region, including the Trans-Antarctic Mountains and Commonwealth Bay; the remains of two ships, *Antarctic* and *Endurance,* in the Weddell Sea off the Antarctic Peninsula; and artifacts and a tractor on the sea floor at Cape Evans, Ross Island.
- Wooden huts, middens, and equipment associated with sites occupied during the British "Operation Tabarin 1" (1943–1944), the United States Antarctic Service Expedition (1939–1941), the Finn Ronne Antarctic Research Expedition (1947–1948), and the former United States (1957–1959)/Australian (1959–1960) Wilkes Station.

The sub-Antarctic islands, which include six groups between latitudes 50°–60° S and the more temperate island groups south of New Zealand (Campbell, Auckland, Bounty, Antipodes, and the Snares), all have important archaeological sites associated with sealing, whaling, farming, and science. Included are try works and remains of huts, castaway depots, cemeteries, and villages. On Auckland Island is located the extensive Enderby settlement, a cemetery, and sites of military significance, from the "Coast Watchers" in World War II.

In the 1960s, when New Zealand field parties removed ice from within three huts associated with the expeditions of Carsten E. Borchgrevink (1899–1900), Robert Falcon Scott (1901–1904 and 1910–1913), and Ernest Shackleton (1908–1909 and 1914–1917), there was little emphasis on archaeology as we know it today. Excavation methods were essentially the use of pick and shovel with the main emphasis on artifact recovery and making the huts snow-proof. Only sparse records were maintained and artifact conservation was not thought of. Subsequent work also saw considerable information lost during the clearance of middens about the huts that had the potential to provide significant knowledge on the occupation and privations suffered by early expeditions, and locations of artifacts about the huts was seldom recorded.

In the late 1970s, however, New Zealand led the way when for the first time systematic archaeology was demonstrated outside Scott's hut at Cape Evans. This pioneering work, which involved the use of heavy black polythene to help thaw surface deposits and the detailed recording of many artifacts located in the volcanic scoria, was followed closely in January 1978 by Australia, at Mawson's huts on Cape Denison, Commonwealth Bay. Here artifacts located inside the ice-filled huts were carefully documented and replaced in their original position, and the work was recorded on plans and with video and still film.

The establishment in New Zealand of a Historic Sites Management Committee in 1980 led to the compilation of the first Management Plan for the huts erected by Scott and Shackleton on Ross Island. This in turn resulted in the formation in 1987 of the Antarctic Heritage Trust and guidelines determining how future archaeological work should be undertaken. In the period 1988–1990, archaeologists using a range of equipment including a small electric percussion drill, excavated a stores annex and stables at Cape Evans and the unroofed "stores hut" at Cape Adare.

At Cape Denison Australian archaeologists working alongside artifact conservators in the 1990s introduced an important new phase in the way in which excavations were undertaken at historic sites. On Livingston Island, South Shetland Islands, a comprehensive survey of early sealing sites and shipwrecks was completed in 1957–1958 by scientists from the British Antarctic Survey and further work has been done by scientists from Chile. Since 1988, archaeologists from Argentina have removed ice from the wooden hut built on Snow Hill Island for Otto Nordenskjold's Swedish South Polar expedition (1901–1904). Further artifacts were removed from Nordenskjold's rock hut on Paulet Island; however, no detailed plans were compiled for either archaeological site.

Historical archaeology also includes site surveys, and, with support from the British Antarctic Survey and the United States National Science Foundation, artifacts at Port Lockroy on Gauvier Island and at East Base on Stonington Island have been carefully documented. With exception of some recording within the remains of a hut at Port Lockroy built for Operation Tabarin 1, no archaeological excavations have been carried out.

On the sub-Antarctic islands, extensive recording of historic sites associated with sealers and some archaeological work on hut remains has been done by Australian scientists on Macquarie Island and on Heard Island. Field work on New Zealand's sub-Antarctic islands has been mostly concerned with site surveys and documentation.

In contrast to work done at temperate latitudes, field work in Antarctica is restricted to a few weeks each summer and is reliant on fine weather. While much has already been achieved at the key historic sites, there is still potential for further work; however, sites such as Cape Adare, Cape Denison, and Cape Evans (the largest site from the Heroic Era) must each be treated differently. They have a variety of problems that determine how archaeology can be done and these range from the effects of penguin guano and fungi on artifacts and the huts to metal corrosion, the effects of ultraviolet light, high relative humidity, damage by wind, and unknowing damage by visitors from tour ships and national programmes. Recent sites such as East Base and the former Wilkes Station also offer great possibilities for historic archaeology.

Strict controls are now in place for any work through national programmes, and all archaeology at historic sites, whatever it may be, must be weighed against the relevant conservation plans for the sites, formally sanctioned, and subject to permits. In Antarctica all historic sites are protected by the 1991 Protocol on Environmental Protection to the Antarctic Treaty, while historic sites on sub-Antarctic islands are protected by legislation of the country responsible for the islands. In the case of New Zealand this is by the Department of Conservation, which limits numbers of visitors and also issues permits for any archaeology. It is vitally important that all archaeological work, including excavation, takes into consideration the ICOMOS 1990 Charter for the Protection and Management of the Archaeological Heritage.

Historical archaeology in Antarctica and the sub-Antarctic can provide a better understanding of the cultural heritage and while there is a great future for the discipline, it can be argued that this may always remain second to such sources as published works, diaries and other manuscripts, and museum collections.

David L. Harrowfield

See also **Antarctic Peninsula; Protected Areas Within the Antarctic Treaty Area; Australasian Antarctic Expedition (1911–1914); British Antarctic *(Nimrod)* Expedition (1907–1909); British Antarctic *(Southern Cross)* Expedition (1898–1900); British Antarctic *(Terra Nova)* Expedition (1910–1913); British Antarctic Survey; British National Antarctic *(Discovery)* Expedition (1901–1904); Deception Island; History of Antarctic Science; Imperial Trans-Antarctic Expedition (1914–1917); Mawson, Douglas; New Zealand: Antarctic Program; Nordenskjöld, Otto; Protocol on Environmental Protection to the Antarctic Treaty; Ronne Antarctic Research Expedition (1947–1948); Scott, Robert Falcon; Sealing, History of; Shackleton, Ernest; South Georgia; South Shetland Islands; Swedish South Polar Expedition (1901–1904); United States Antarctic Service Expedition (1939–1941); Whaling, History of**

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ARCTIC AND ANTARCTIC RESEARCH INSTITUTE, RUSSIA

The Arctic and Antarctic Research Institute (AARI) in St. Petersburg originated as the Northern Scientific Commercial Expedition on March 4, 1920. In 1925, the Expedition became the Institute of Northern Studies, and in 1930 the All-Union Arctic Institute. In 1939, it was renamed the Arctic Research Institute. In 1958, by the decision of the government of the USSR, it was entrusted with organization and coordination of national studies and operations in the Antarctic, after which it received its present name. In 1963, AARI was placed under the control of the Main Administration of the Hydrometeorological Service of the country (present Federal Service for Hydrometeorology and Environmental Monitoring).

AARI is one of the world's largest centers of polar scientific research. It became widely known in the 1930s after conducting numerous successful Arctic expeditions in the marginal Siberian shelf seas and the central Arctic Basin. These include the first voyage of the icebreaking vessel *Sibiryakov* (1932) in one summer navigation period from Arkhangelsk to Vladivostok, organization of the first drifting North Pole station (1937–1938), and an airborne expedition to the area of the Pole of Relative Inaccessibility (1941). One of the major directions in AARI's activity since the 1930s has been providing scientific-operational information and forecasts on the state of water, ice, and atmosphere along the Northern Sea Route. In the 1970s, such navigation on some segments of this route was year-round. In support of shipping, detailed investigations were made on the peculiarities of ice regimes, tides, sea-level oscillations, currents, waves, physical and mechanical ice properties, and characteristics of the ice performance of different types of ships in the Siberian shelf seas and river mouths.

Full-scale materials for scientific studies of the Institute were collected by means of numerous drifting, marine, airborne, river, and land expeditions over the entire far north of the country and in the near-pole areas of the Arctic. In addition, data of coastal and island polar stations and transport vessels and icebreakers were subjected to scientific analysis and generalization. In the 1970s and 1980s, the Arctic region covered by scientific studies by AARI was significantly expanded when a fleet of seven research vessels was built for the Institute. The Greenland and Norwegian seas and the North Atlantic were a major study area at that time. Comprehensive large-scale experiments were conducted throughout the entire Arctic aiming to reveal the natural ocean–atmosphere interaction mechanisms in the region. These studies were called the Polar Experiment–North. As a result, the processes of genesis and transformation of water masses, specific features of water circulation and ice, and their seasonal and interannual variability were investigated. Main regularities and types of the atmosphere circulation, their relations to the helio-geophysical processes, characteristics of the Arctic Ocean freshwater balance, etc., were determined.

Modern scientific studies of AARI in the Arctic are conducted within a wide range of Earth sciences: climatology, meteorology, oceanography, land water hydrology, geophysics, ecology, glaciology, geomorphology, sea-ice/offshore structure interaction, and polar medicine.

The AARI staff began regular studies in the Antarctic in 1956 within the framework of the national Arctic expeditions of the USSR Academy of Science. Since 1958, the activities of the Russian (Soviet) Antarctic Expedition (RAE) have been organized and coordinated directly at AARI. These functions are fulfilled by the departments of logistics support and perspective planning of RAE activity. The AARI specialists participated directly in the discovery and study of many geographical features of East Antarctica. When the geographical stage of studies of Antarctica was replaced by investigations of the regular features of formation and variability of natural processes, the Institute's scientific programs began to play the leading role in the national Antarctic program of the country. Studies in meteorology, aerology, oceanography, geomagnetism, structure and dynamics of the ionosphere and ozonosphere, limnology, glaciology, geomorphology, paleoclimatology, and polar medicine that were mainly performed by AARI staff allowed a detailed investigation of the main environmental compartments of the region. The results of these studies were published in two volumes of the Atlas of the Antarctic (1966 and 1969), which received wide recognition among scientists in many countries.

The AARI staff has become most renowned for the results of the cycle of studies of structure and dynamics of geomagnetic processes in polar caps when a specially developed PC index was proposed as an integral numerical indicator of the magnetic perturbation state. Another example is a wide known curve of four paleoclimatic cycles obtained from the ice core data at Vostok station for the last 420 kyr. Studies of crystalline composition and gaseous content of congelation ice from the lower horizons of Vostok ice core formed of frozen water of the subglacial Lake Vostok have won worldwide recognition. Modern AARI research in the Antarctic is carried out within the framework of the subprogram "Study and Research of the Antarctic" of the Federal Program "World Ocean" where the Institute is a principal executor in fourteen of nineteen projects in the direction "Fundamental studies." These are studies of the processes of current climate formation and its future changes, determination of the climate-forming role of the Southern Ocean, studies of paleoclimatic changes based on ice-core data from deep boreholes and bottom sediments of the water bodies, study of the subglacial Lake Vostok, assessment of the structure and dynamics of geophysical processes in polar caps, mechanisms of impact of helio-geophysical perturbations on living organisms, study of aerosol-optical properties of the atmosphere, and generation of the geoinformation system of Antarctic data. The activities in the direction of the subprogram "Scientific-applied studies and developments," "Monitoring of natural media of the Antarctic," "Environmental protection" and "Logistics support for operation of the Russian Antarctic Expedition" are carried out by AARI staff in the RAE structure.

At the present time, the AARI staff numbers 880 specialists, among which 330 work at seventeen scientific departments of the Institute. In addition to scientific departments, the Institute's structure includes RAE, Fleet Department, and Center of Ice and Hydrometeorological Information "Sever." The AARI runs the R/V *Akademik Fedorov* and *Professor Multanovsky*.

The experimental ice tank operates at the Institute testing models of ships and engineering structures.

AARI has wide international relations actively cooperating with research institutions of Australia, Germany, Norway, the United States, France, and Japan. The Institute's structure includes the Russian-German and the Russian-Norwegian Scientific Laboratories where joint studies are conducted and where young scientists of these countries work under special grants.

In 1994, AARI was assigned the status of the State Research Center—the highest level of recognition of research institution in Russia regardless of its agency affiliation.

In different years, such prominent polar explorers as Rudolf Samoilovich, Vladimir Viese, Viktor Buinitsky, Georgy Vangengeim, Alexander Girs, Pavel Gordienko, Mikhail Somov, Aleksey Treshnikov, and Yevgeny Korotkevich worked at AARI.

VALERIE LUKIN

See also **Climate Change; Ice Core Analysis and Dating Techniques; Lake Vostok; Russia: Antarctic Program; Sea Ice: Types and Formation; Sea Ice, Weather, and Climate; Subglacial Lakes; Vostok Station**

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ARCTIC TERN

The Arctic tern *(Sterna paradisaea)* has a circumpolar distribution, breeding abundantly in the Arctic and sub-Arctic regions of Europe, Asia, and North America in colonies on coastlines, islands, and occasionally inland on tundra near water. During the nonbreeding period, Arctic terns migrate annually to as far south in the Southern Hemisphere as the edges of the Antarctic pack ice.

This species is highly migratory, flying from its Arctic breeding grounds to its wintering areas in the Antarctic. This migration ensures that this bird sees more daylight than any other creature on the planet. The journey, of at least 19,000 km one way, is the longest known migration of any species. One particularly spectacular example was of an Arctic tern banded as a chick, not yet able to fly, on the Farne Islands off the Northumberland coast of eastern England in the summer of 1982. This bird reached Melbourne, Australia, in October of the same year, having flown over 22,000 km in just 3 months from fledging—an average of over 240 km per day and one of the longest journeys ever recorded for a bird. The length of this migration suggests that in its lifetime an average Arctic tern will travel a distance equal to going to the moon and back.

The nonbreeding areas in the Antarctic pack-ice zone are mainly between 55° E and 155° E in the Indian Ocean sector, but the species has been seen all around the Antarctic continent. There are two main migratory routes: from breeding sites in Siberia and Alaska southward along the Pacific coasts of North and South America (in limited numbers also across the central Pacific) between August and December, then across the Drake Passage to Antarctica. Birds from Atlantic breeding places in North America, Greenland, islands in the Northern Atlantic Ocean, Europe, and coastal Siberia migrate over the Atlantic Ocean near western Europe and West Africa, partly in a broad front or crossing the Southern Ocean. Few birds have been reported in the Indian Ocean. Circumnavigation of the Antarctic continent has been reported, and some of the nonbreeders remain in the Southern Hemisphere and do not migrate to the north.

Breeding Behaviour

Egg laying takes place from May to July, depending on the latitude of the breeding locality, air temperature, and food availability, in colonies ranging in size from just a few to 300 pairs. Two to three eggs are laid and incubated for 22–27 days. The chicks fledge after 21–24 days. The Arctic tern is the most aggressive tern, fiercely defensive of its nest and young. It will attack humans and other large predators, usually striking the top or back of the head. Although it is too small to cause serious injury, it is capable of drawing blood.

Like all *Sterna* terns, the Arctic tern feeds by plunge-diving for fish, usually from the sea, although occasionally also fishing in coastal freshwater lagoons. It often dives from a "stepped-hover." The offering of fish by the male to the female is part of the courtship. In the Antarctic, Arctic terns feed in water near the edge of pack ice, especially between ice floes. They mostly take food from just below the water surface by dipping. They feed on fish, crustaceans (copepods, amphipods, and also krill), and, in the Arctic, on insects.

HANS-ULRICH PETER

See also **Antarctic Tern; Kerguelen Tern; Terns: Overview**

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ARGENTINA: ANTARCTIC PROGRAM

Argentine Antarctic activities started early in the nineteenth century when sealers and whalers sailed south of South America looking for new hunting areas. Scientific activities started at the beginning of the twentieth century when José María Sobral (later PhD in geology from the Uppsala University in Sweden) joined the Swedish South Polar Expedition (1901–1904) commanded by Otto Nordenskjöld, which wintered two years in Antarctica. Around the same time, W. S. Bruce, leader of the Scottish National Antarctic Expedition, turned over to Argentina the meteorological and geomagnetic observatory (today Orcadas Station) located on Laurie Island, South Orkney Islands; this observatory continues to run at the start of the twenty-first century, having run without interruption for more than a century. In 1951, Argentina set up the first worldwide institution fully dedicated to Antarctic research: the Instituto Antártico Argentino (IAA). Logistic operations started with the rescue of the Nordenskjöld expedition carried out by the Argentine Navy's corvette *Uruguay* under the command of Lieutenant Julian Irizar in 1903.

The Argentine Antarctic Program is composed of several organizations forming the highest levels of the National Government. Logistics are provided by the Argentine Army, under the Defense Ministry, whereas all other activities are ruled by the Dirección Nacional del Antártico–Instituto Antártico Argentino of the Ministry of Foreign Affairs. The program spends approximately the equivalent of \$10 million to \$12 million US each year for Antarctic activities. The purpose of the Argentine Antarctic Program is to support, strengthen, and increase the Argentine sovereign claims over the portion of the Antarctic continent and surrounding seas from 25° W to 74° W and from 60° S to the Pole ("Sector Antártico Argentino").

Argentina is the closest country to Antarctica and runs six permanent scientific stations, the most of any country. They are Orcadas (60°44′ S, 44°44′ W), Laurie Island, South Orkney Islands; Jubany (62°14′ S 58°40′ W), King George (25 de Mayo) Island, South Shetland Islands; Esperanza (63°24′ S, 57°00′ W), Hope Bay, northern tip of the Antarctic Peninsula; Marambio (64°14′ S, 56°38′ W), Seymour (Marambio) Island, northwestern Weddell Sea; San Martín (68°08′ S, 67°06′ W), Barry Island, Margarite Bay, and Belgrano II (77°52′ S, 34°37′ W), Bertrab Nunatak, southeastern Weddell Sea. Additionally, Argentina maintains seven seasonal (nonpermanent) stations: Brown (64°53′ S, 62°53′ W), Paradise Cove; Primavera (64°09′ S, 60°58′ W), Danco Coast; Decepción (62°59′ S, 60°41′ W), 1° de Mayo Bay, Deception Island; Melchior (64°20′ S, 62°59′ W), Observatory Island, Melchior Archipelago; Matienzo (64°59′ S, 60°07′ W), Larsen Nunatak, Weddell Sea; Cámara (62°36′ S, 59°56′ W), Half Moon Island, South Shetland Islands; and Petrel (63°28′ S, 56°12′ W), Welchness Cape, Antarctic Strait.

Orcadas Station is the oldest Argentine station in the Antarctic, and Marambio the newest and the only one built after the Antarctic Treaty was signed. It has a dirt airstrip that allows year-round landing of heavy-duty planes with conventional wheels (C-130 Hercules) carrying up to 12 tons of cargo. Belgrano II is the southernmost active station in the Weddell Sea area and the departure and return point of the two land-traveled Argentine expeditions to the South Pole carried out up to now.

The logistic support for Antarctic activities is provided by the Argentine Army. The Argentine Navy runs Orcadas Station and operates a large icebreaker named *Almirante Irizar,* built 25 years ago in Finland specially for the Argentine Antarctic Program; an oceanographic vessel *(Puerto Deseado);* and several smaller patrol vessels. The icebreaker brings two heavy-duty Sea King–type helicopters. Air operations from South America and within Antarctica is provided by the Argentine Air Force through several C-130 Hercules planes, a small DHC-6 Twin Otter plane year round based on Marambio Station, and Bell 212 helicopters deployed in Marambio Station during the summer. The Argentine Army provides support running three permanent stations (including the two southernmost ones) and supporting scientific land expeditions. The Dirección Nacional del Antártico operates Jubany Station and provides logistic support to the scientific field camps and refugees. Jubany Station holds the Argentine-German Dallmann Laboratory dedicated to marine biology and geological studies.

The science program is run by the Instituto Antartico Argentino (IAA). The scientific priorities were set according to the National Antarctic Policy to investigate, understand, and preserve natural resources, to protect the environment, and to maintain the historical monuments. Accordingly, the main research lines are focused on fisheries, marine ecosystems, mineral resources, climate change, environmental protection, and history of human activities in Antarctica. To accomplish this task the IAA is comprised of scientific departments (biology, geology, glaciology, oceanography, etc.) grouped into three major areas: life sciences, Earth sciences, and ocean and atmospheric sciences. The research programs, run by members of the IAA permanent staff, are open to any scientist from Argentina. Presently the IAA scientific program consists of more than thirty research projects and fifteen scientific activities carried out in cooperation with other national (mainly universities and the Argentine National Council of Sciences) and international (US, France, Germany, Italy, Spain, Japan, Canada) scientific institutions.

Sergio A. Marenssi

See also **Antarctic: Definitions and Boundaries; Antarctic Peninsula; Antarctic Treaty System; Aviation, History of; Bruce, William Speirs; Deception Island; Geopolitics of the Antarctic; King George Island; Nordenskjöld, Otto; Scottish National Antarctic Expedition (1902–1904); Sealing, History of; South Orkney Islands; South Shetland Islands; Swedish South Polar Expedition (1901–1904); Swedish South Polar Expedition, Relief Expeditions; Whaling, History of**

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ART, ANTARCTIC

Because the physical environment of the Antarctic is so foreign to human experience, most of the art made about it by the fewer than two hundred artists to have visited the continent has been landscape work with a strong topographical nature, in particular panoramic views. In addition there have been various records of the expedition activities as well as some important natural history illustrations recording new species.

The first artist to cross inside the Antarctic Circle was William Hodges (1744–1797), a classically trained British landscape painter who sailed on Captain James Cook's second voyage to the Pacific Ocean in 1772. Although they never sighted the continent itself, Hodges painted the panoramic coastal profiles required by the Royal Navy as far as the island of South Georgia, as well as images detailing ships among icebergs.

During the nineteenth century expedition leaders such as the Frenchman Jules-Sébastien-César Dumont d'Urville and the American Charles Wilkes made paintings and drawings, as did their artists, who included Louis Le Breton and Alfred Agate, the latter being the first to picture the continent itself in 1840. J. E. Davis, sailing under James Clark Ross into the Ross Sea during 1841, made views of the Great Ice Barrier, Mount Erebus, and Ross Island. The first significant Antarctic artist, however, was Dr. Edward Wilson, who served as physician to both of Scott's expeditions. A self-trained artist strongly influenced by J. M. W. Turner, he created extensive topographical profiles in the Ross Sea region, but also more than 400 finished natural history and landscape paintings. There have been several other talented amateurs over the last century.

Photography was first used in the Antarctic in 1874, and by the turn of the century was extensive. Photographers Herbert Ponting with Scott's second expedition and Frank Hurley with Shackleton defined the Heroic Age of Antarctic exploration with romantic images of ships frozen into the ice. Swiss photographer Emil Schulthess brought modern photography to the continent during the International Geophysical Year (1957–1958), and was followed by noted color photographer Eliot Porter in 1975.

Edward Seago, better known for his British landscapes and circus paintings, visited the Antarctic Peninsula in 1956. During the 1960s, two Australian painters broke away from the topographical style of earlier artists. Sydney Nolan introduced expressionism as a way of interpreting the Antarctic, and Nel Law produced abstractions of ice patterns. Visiting artists programs administered by national Antarctic programs subsequently broadened the aesthetic range. Although landscapes by painters such as David Robertson (US), David Smith (UK), and Keith Grant (UK), and photographers Neelon Crawford and Jody Forster (US) continue to dominate Antarctic art, more contemporary painters such as Nigel Brown, Margaret Eliot (NZ), and John Jacobsen (US) have expanded the expressive interpretation of the continent. Panoramic photographs by Stuart Klipper (US) and minimalist studies by Anne Noble (NZ), the modernist sculptures of Gabriel Warren (US), installation work of Virginia King (NZ), and mixed-media work by Stephen Eastaugh (AUS) and John Kelly (UK) have created an Antarctic art that is less representational and more symbolic, an aesthetic evolution that demonstrates increasing familiarity with the continent by both artists and audiences.

WILLIAM L. FOX

See also **Fiction and Poetry; Film; Music, Antarctic; Photography, History of in the Antarctic**

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ASTRONOMICAL OBSERVATIONS FROM ANTARCTICA

Astronomy is the study of the universe in which we live. In recent years there has been rapid progress in the understanding of the cosmos, with the first detections of planets around other stars, of a black hole in the centre of our own galaxy, and of a mysterious "dark energy" that appears to be repelling galaxies. However, many important questions remain, ranging from fundamental questions about the origin, structure, and evolution of the universe to perhaps the most exciting question of all: Are we alone in the universe, or do some of the recently detected planets around other stars harbour alien life?

In the quest to provide answers, astronomers observe over the full range of the electromagnetic spectrum, from radio waves to high-energy gamma rays. Astronomy has traditionally progressed by building bigger and better telescopes and deploying them to the best observing sites known. Antarctica—and particularly the high Antarctic Plateau—offers many advantages to astronomy. Many of these advantages are associated with minimising the corrupting effects of the Earth's atmosphere. The atmosphere does three undesirable things. First, it absorbs some of the radiation from the astronomical object, reducing its intensity and, at some wavelengths, rendering the object completely unobservable. Second, it emits its own radiation, particularly in the infrared, creating an unwanted background signal. Finally, the fluctuations in the refractive index of the air, principally as a result of turbulent cells of differing temperature, cause blurring and other unwanted effects on the images.

Placing a telescope in space has the obvious advantage that there is no atmosphere. For some observations, for example in the study of x-rays and gamma rays, there is no alternative to a space-borne observatory. However, the cost of a space observatory is ten to one hundred times that of a ground-based one, providing a powerful incentive to astronomers to take advantage of the best ground-based sites available.

Although the South Pole was recognised as a potentially useful observing site for many years, it was not until 1979 that the first optical observations were carried out there, by a US/French team. This research, led by the US astronomer Martin Pomerantz, took advantage of the continuous daylight at the South Pole during the summer to study the sun for long, unbroken periods.

A few years later, a pioneering experiment to study submillimetre wavelength emission from the Galactic Plane was set up at the South Pole. In the years that followed a gradual buildup of astronomical facilities took place, largely as a result of the activities of the US Center for Astrophysical Research in Antarctica (CARA), which established telescopes spanning the spectrum from millimetre waves to the infrared.

Optical

For optical astronomers the main advantage of Antarctica is the extreme stability of the atmosphere. The high plateau of Antarctica has the lowest wind speeds on earth, in stark contrast to the coast where winds can exceed 300 km/hr. Low surface wind speeds allow a simple telescope and dome structure to be constructed. More important, however, is that the wind speed above the Antarctic Plateau is usually very low throughout the entire thickness of the atmosphere. It is the turbulent mixing of air of different temperatures that the wind inevitably creates that leads to a degradation of image quality.

This image degradation, known as "seeing," sets a limit to the resolution of an optical telescope. Measurements of the atmospheric turbulence above the Antarctic Plateau site, Dome C, by groups from France and Australia have shown that the seeing is substantially better than anywhere else on Earth—a factor of 2–3 times better than at the best observatory sites in Chile, Hawaii, and the Canary Islands. On some occasions, the atmosphere becomes so stable that images comparable to those from the Hubble Space telescope should be obtainable.

An effect related to seeing, but dependent more on the amount of high-altitude turbulence, is the constant fluctuation in the observed intensity of a star, known as scintillation. This familiar "twinkling" of stars is greatly reduced in Antarctica, making it an ideal location for precision measurements of stellar brightness.

A recent development in astronomy is the use of adaptive optics. In this technique the shape of a flexible mirror is altered at high speed in response to atmospheric fluctuations. By reflecting the light from the star from this adaptive mirror, the effects of atmospheric turbulence can be at least partially eliminated. Only with the help of an advanced adaptive optics system will astronomers be able to take full advantage of the next generation of extremely large telescopes (ELTs). The low wind speeds throughout the Antarctic atmosphere, combined with the already very stable turbulence structure, imply that the Antarctic Plateau may be the best location for these huge telescopes.

One of the most advanced of the ELT designs is a 21-metre diameter optical telescope called the Giant Magellan Telescope, to be built in northern Chile. A second version proposed for Antarctica would be easily the most powerful telescope in the world, with a unique ability to detect Earth-like planets around other stars and probe the earliest stages of the universe.

Infrared

Infrared astronomy, where the heat radiation from a star is observed, is extremely difficult from a ground-based site. This is not only because large regions of the infrared spectrum are blocked by absorption in the Earth's atmosphere, but because the atmosphere (and even the telescope itself) emits strongly in the infrared. This additional "background" emission reduces the sensitivity of the telescope to the true astronomical signal. For infrared astronomers the Antarctic Plateau has the advantage that it is very cold and exceedingly dry. Both of these things contribute to better atmospheric transmission and to a lowering of the background emission from the telescope and the sky by as much as a factor of 100. The first infrared telescope to explore these conditions was SPIREX (South Pole Infrared Explorer), a 60 cm infrared reflector that operated at the South Pole from 1993 to 1999.

Submillimeter

Submillimeter astronomy, in the frequency range 0.3–10 THz (wavelengths of 1 mm–30 microns) is extremely difficult from a ground-based observatory because of absorption by water vapour in the Earth's atmosphere. For this reason, almost all submillimeter astronomical research to date (especially at frequencies above 1 THz) has been from high-altitude balloons, from stratospheric aircraft, or from space. The air above the Antarctic Plateau is extremely dry, containing one tenth to one one-hundredth as much water as the air at temperate sites. This opens up new observing "windows" at wavelengths opaque from other sites. Dome A, at 4100 m the highest point of the plateau, is expected to be the best observing site on Earth for terahertz astronomy.

The Antarctic Submillimeter Telescope and Remote Observatory's (AST/RO) submillimeter telescope, with a 1.7 m diameter off-axis dish, has operated at South Pole since 1995.

Microwave and Millimetre Waves

Studies of the cosmic microwave background (CMB) give information about the early universe. This all-pervasive radiation, discovered by Penzias and Wilson in 1965, gives a unique view of the universe when it was a mere 400,000 years old. Although remarkably uniform in distribution and appearing to have a single, well-defined temperature of 2.7 K, the CMB shows minute deviations from uniformity and from a pure blackbody spectrum. Studying these deviations requires an observing site that is clear, transparent, and extremely stable.

The Degree Angular Scale Interferometer (DASI) experiment at the South Pole is one example of how the improved observing conditions in Antarctica can lead to crucial breakthroughs: DASI was the first experiment—ground-based or in space—to detect polarization in the CMB.

Yet another way of studying the CMB is with a long duration balloon (LDB), which takes advantage of the stable and predictable high-altitude winds that circulate around the coast of Antarctica. Launched from an appropriate site such as McMurdo, an LDB can travel around the continent before returning to the launch site some two weeks later. In this way astronomers can obtain hundreds of hours of data from a single flight. The BOOMERanG experiment, a collaboration between Italian and US teams, has shown how effective this technique can be for CMB studies, producing the important result (subsequently confirmed by the space mission WMAP), that the universe is geometrically "flat." This result implies that 90% of the universe consists of something we currently know almost nothing about, while the observable universe of stars, gas, and dust accounts for a mere 10% of its mass.

An important future development for CMB studies is the South Pole Telescope (SPT), currently under construction. The telescope is a 10 metre diameter off-axis paraboloid dish optimised for cosmological studies.

Particle Astronomy

Another tool available to astronomers is particle astronomy, which studies cosmic rays and elusive subatomic particles such as neutrinos. Cosmic ray research was amongst the first scientific studies to be carried out in Antarctica. Neutron and muon detectors have operated continuously at the coastal station of Mawson since 1956. For the most part, it is Antarctica's geographic location that is favoured. However, at the South Pole the vast volume of pure ice has been put into service as AMANDA (Antarctic Muon and Neutrino Detector Array). This project, which has operated now for a decade, consists of hundreds of photomultiplier tubes lowered into bore holes in the ice. AMANDA detects the Cerenkov radiation of relativistic muons created when neutrinos interact with matter. An even more ambitious neutrino detector, IceCube, will place photomultipliers into the ice throughout a volume of 1 cubic kilometre, giving a major increase in sensitivity.

Meteorites

Meteorites, preserved where they fall in the pristine snow of Antarctica, can be used to trace the chemical and physical history of the solar system. The first such meteorite was discovered by members of Douglas Mawson's Australasian Antarctic Expedition in 1912. More recently, astrogeologists have taken advantage of the concentrating effect of ice movement and sublimation to find accumulations of meteorites in particular locations. It was in the Allan Hills meteorite field that the Martian meteorite ALH 84001 was discovered in 1984. Microscopic structures within the meteorite led to speculation, still not fully resolved, that they represented an ancient form of Martian bacteria.

Disadvantages

Operating an astronomical observatory in Antarctica is more difficult than at a temperate or tropical site. Special measures are required to allow the telescope to operate reliably at the very low temperatures. Antarctic stations, although operated year-round, are cut off from the rest of the world for six months or more each year. As well as logistic difficulties there are also some astronomical limitations. Less of the sky is visible from Antarctica than from sites closer to the equator. In addition, there is less truly "dark" time, as the sun spends a smaller fraction of the time well below the horizon. Aurora and other forms of airglow are detrimental to optical astronomy, although their impact has yet to be properly quantified.

Observing Sites

The US-operated Amundsen Scott Station at the geographic South Pole is currently host to Antarctica's most comprehensive astronomical observatory. Viewed from the South Pole, all celestial objects beyond the solar system move across the sky at constant elevation. This is particularly advantageous for studies of the CMB and for detailed studies of how the light from individual stars varies over time.

Concordia Station, at Dome C, was opened for year-round operation in 2005. This joint French/Italian facility will support a variety of research programs, including astronomy. Already proposals have been made to construct optical telescopes there of over 2 metre diameter, as well as submillimeter telescopes and interferometers. At 3250 m elevation, Dome C is higher, colder, and drier than the South Pole. In addition, the wind speed and the low-altitude turbulence is significantly lower.

Other potential observing sites include the Russian station at Vostok, the Japanese station at Dome F, and the highest point on the plateau, Dome A.

John Storey

See also **Amundsen-Scott Station; Astronomy, Infrared; Astronomy, Neutrino; Astronomy, Submillimeter; Aurora; Australasian Antarctic Expedition (1911–1914); Cosmic Rays; Mawson, Douglas; Meteorites; South Pole; Vostok Station; Wind**

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ASTRONOMY, INFRARED

In order to learn as much as possible about astronomical objects such as planets, stars, and galaxies, astronomers observe them at a variety of wavelengths. Infrared radiation is invisible to the unaided eye, but carries a wealth of information about objects in the universe. However, observing in the infrared from ground-based telescopes is challenging, for the simple reason that the Earth's atmosphere and the telescope itself both emit copious quantities of infrared radiation that can overwhelm the small signals from space; an analogy is attempting optical astronomy in broad daylight with a telescope that is made from fluorescent light tubes. The obvious solution to this problem is to take the telescope to a very cold observing site, such as Antarctica.

While the potential benefits of Antarctica for infrared astronomy were realised by the 1980s, it wasn't until the early 1990s that US and Australian astronomers deployed experiments to test the quality of the sites, and to ascertain the practical difficulties of operating telescopes there. The first infrared telescope in Antarctica was the 0.6 meter South Pole Infrared Explorer (SPIREX), which operated at the US Amundsen-Scott South Pole Station from 1993 until 1999. From 1994 to 1996, the IRPS experiment measured the near-infrared sky brightness at the South Pole; later in the 1990s NIMPOL (for N-band Imaging Polarimeter), SPIRAC (for South Pole Infrared Array Camera), and AASTO (for Automated Astrophysical Site-Testing Observatory) extended this data to longer wavelengths. These experiments showed that Antarctica offers factors of at least 10, and up to 100, reduction in the infrared signal from the Earth's atmosphere when compared with temperate latitude observing sites. Furthermore, the atmospheric signal is very constant with time, making it much easier to correct for.

SPIREX and other experiments also showed that the turbulent layer of air in the lowest 200 meters at the South Pole results in star images that are somewhat blurrier than those taken from temperate observatories. This fact effectively thwarted plans for building a large infrared telescope in Antarctica, and it wasn't until 2004 that enthusiasm was rekindled following the confirmation by French and Australian astronomers of spectacularly low levels of turbulence at the Franco-Italian Concordia Station at Dome C, a location on the high Antarctic Plateau at a latitude of 75° S. The next step in the development of infrared astronomy from Antarctica may well be a 2 meter aperture telescope at Dome C, followed by a 4 meter and then an 8 meter. Other sites on the Antarctic Plateau, such as Dome A and Dome F, are also potentially excellent, although they currently lack the infrastructure to support an observatory.

The unique atmospheric conditions above the Antarctic Plateau also offer exciting advantages for infrared interferometry. An interferometer consists of two or more telescopes separated by perhaps 100 meters, and could be used to directly image planets orbiting around stars other than the Sun. Interferometers can also detect planets indirectly by observing the very small changes in the relative positions of stars as planets orbit around them. This latter technique benefits greatly from the stability of the atmosphere above high plateau sites such as Dome C.

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See also **Amundsen-Scott Station; Astronomical Observations from Antarctica; Astronomy, Submillimeter**

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ASTRONOMY, NEUTRINO

The Universe is the site of nuclear processes more violent than those created by earthbound particle accelerators. Nature accelerates cosmic elementary particles to energies in excess of 10^{20} electron volts, a macroscopic energy of 50 joules carried by a single elementary particle. It is not known where these particles originate or how they are accelerated. Because such "cosmic rays" are electrically charged, their paths are scrambled by galactic and, in some cases, intergalactic magnetic fields so their arrival directions at Earth do not reveal their origin. The puzzle persists almost a century after the discovery of cosmic radiation. Cosmic rays are poor astronomical messengers for another reason—they self-destruct in collisions with microwave photons to vanish into electrons and positrons. They therefore only reach Earth from the nearby cosmic neighborhood. They share this problem with photons, the particles of light, thus essentially eliminating conventional astronomical techniques. The Universe, as revealed by photons and protons, is mostly obscured from view at these high energies.

Since its discovery in the 1950s in the radiation of nuclear reactors, the neutrino has been recognized as the ideal particle for this "extreme" astronomy. With essentially no mass and no electric charge it matches the photon as a cosmic messenger. It differs in one important attribute, however: Its interactions with matter are extremely feeble, even allowing high-energy neutrinos to reach Earth unscathed from the edge of the universe and the inner neighborhood of black holes and, hopefully, from the nuclear furnaces where cosmic rays are born. They may give information about cosmic sites never "seen."

In summary, neutrinos can reach Earth undeflected and unabsorbed, even from optically shrouded sources. Unfortunately, their feeble interaction with matter makes cosmic neutrinos also very difficult to detect; trillions fly through every individual's body every second, at most a few will stop in a lifetime. Immense particle detectors are required to collect them in sufficient numbers to do science. One possibility has been to transform the deep Antarctic ice sheet below the South Pole into a neutrino telescope. Even extreme neutrinos will routinely stream through the detectors without leaving a trace; the unlucky one that makes a direct hit on a nucleus in the ice will blow it to pieces creating secondary particles of all kinds. The key is that these will radiate a glow of blue light, dubbed Cherenkov radiation, which will spread through the incredibly transparent natural ice over hundreds of meters. The origin of this radiation is the same as the blue glow shining from the water shielding nuclear rectors. Neutrino astronomers embed optical sensors into Antarctic ice to detect the faint light from a nuclear reaction initiated by a single neutrino.

In general, a neutrino telescope must be:

- Kilometer-size, to detect the low fluxes of neutrinos over cosmic distances;
- Transparent enough to allow light to travel through a widely spaced array of optical sensors;
- Deep, in order to be shielded from surface light and radiation; and
- Affordable.

Only dark oceans and deep glaciers of ice satisfy these constraints. Pure, highly transparent, and free of radioactivity, Antarctic polar ice has turned out to be an ideal medium to detect neutrinos. The difficulty of the remote site has been overcome by exploiting the infrastructure of the US Amundsen-Scott South Pole Station.

An international collaboration has constructed a first-generation neutrino telescope called AMANDA (Antarctic Muon and Neutrino Detector Array). It is the proof of concept for a kilometer-scale neutrino observatory, IceCube, now under construction. Its basic detector component is a photomultiplier housed in a glass pressure vessel, somewhat larger than the size of a basketball. Photomultipliers transform the Cherenkov light from neutrino interactions into electric signals by the photoelectric effect. The signals are captured by a computer chip that digitizes the shape of the current and sends the information to the computers collecting the data, first by cable to the "counting house" at the surface of the ice sheet and then via satellite to the scientists' office computers. One can think of IceCube as 5,000 freely running computers sending information that allows the scientists to infer the arrival directions and energies of the neutrinos. The detector components transform a cubic kilometer of ice at a depth of 1450–2450 meters into a neutrino detector (i.e., one mile below the surface and one quarter mile above bedrock).

Optical sensors produced at collaborating institutions in the United States, Sweden, and Germany are shipped to the international Antarctic center in Christchurch, New Zealand. These are subsequently transported to the South Pole via McMurdo Station. Drillers use a five megawatt jet of hot water to melt a hole in the ice, roughly half a meter wide and 2.5 km deep. Because ice is an excellent insulator, the water does not freeze for several days, ample time to deploy the optical sensors attached to cables that will power them and will also transmit their digital signals to the surface. Each of eighty holes will hold sixty sensors evenly spread over one kilometer between depths of 1450 and 2450 meters.

With some 650 optical sensors in place since February 2000, the AMANDA detector has been collecting neutrinos at a steady rate of four per day. These "atmospheric neutrinos" are the byproduct of collisions of cosmic rays with the nitrogen and oxygen in the atmosphere at the North Pole. Note that at the South Pole one observes neutrinos that originate in the Northern Hemisphere, using the Earth as a filter to select neutrinos. No photons, or any other particles besides neutrinos, can traverse the whole planet to reach the detector. The signals from the atmosphere are not astronomy yet, but they are calculable and can be used to prove that the detector performs as expected.

As in conventional astronomy, AMANDA will have to look beyond the atmosphere for cosmic signals. AMANDA data is now scrutinized for hot spots in the northern sky that may signal cosmic sources. In the south, meanwhile, in 2006, the initial IceCube deployments began augmenting AMANDA. Data obtained less than two weeks after deployment showed that everything was working immediately. A key part of IceCube was IceTop, a surface cosmic-ray air-shower detector array, which was the first part of the project to be installed and will eventually consist of 160 ice-filled tanks distributed over 1 km^2. IceTop will tag IceCube events that are accompanied by cosmic-ray showers, study the cosmic-ray composition up to 10^{18} eV, and serve as a calibration source to tag directionally the cosmic-ray muons that reach iceCube.

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See also **Amundsen-Scott Station; Cosmic Rays; McMurdo Station; South Pole**

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ASTRONOMY, SUBMILLIMETER

Submillimeter (also known as microwave) radiation has a longer wavelength than visible light and occupies the position between the infrared (IR) and radio parts of the electromagnetic spectrum. As the name suggests, this radiation has wavelengths somewhat less than one millimeter (mm): Its range traditionally extends from 1 mm down to around 0.3 mm. It is produced predominantly by atoms and simple molecules inside cool, dense clouds of gas and dust found in between the stars (the interstellar medium) in our own Milky Way as well as external galaxies. These clouds are very important since they represent the raw material from which stars and planets form. It is virtually impossible to study these objects at visible wavelengths since the radiation is almost completely blocked by dust. However, at these longer wavelengths the clouds are more transparent so we are able to study directly the processes occurring inside them.

Submillimeter telescopes look very similar to radio telescopes in that they most commonly use parabolic dishes to collect and focus the radiation. However, due to their shorter wavelengths, the surfaces of the dishes have to be made to much higher accuracies (often to within a few millionths of a meter) compared with the dishes used in radio telescopes. There are two main methods for detecting submillimeter radiation: bolometers, which measure the total intensity of the radiation over a wide range of wavelengths by converting the radiation into heat that is then registered as a corresponding temperature change; and heterodyne receivers, which mix the astronomical signal with an artificially generated signal (the local oscillator or LO) to produce an intermediate frequency (IF), which is then amplified and detected. From this signal a plot of intensity against wavelength (a spectrum) can be extracted over a narrow range of wavelengths. The special mixers used in these receivers employ superconducting junctions that have to be cryogenically cooled to a few degrees above absolute zero (–273°C) with liquid helium (at –269°C).

Submillimeter radiation is very effectively absorbed by water vapor in the lower atmosphere, so it is virtually impossible to detect from sea level. Therefore, submillimeter astronomy can be undertaken only from high and dry observing sites. Good examples are the Caltech Submillimeter Observatory (CSO), the James Clerk Maxwell Telescope (JSMT), and the Submillimeter Array (SMA) facilities, all on the 4000-meter summit of Mauna Kea in Hawaii. However, even at this location observations at these wavelengths are not always possible. An even better place for submillimeter astronomy is the high Antarctic Plateau, where the cold temperatures and dry conditions allow routine observations year round (although observing conditions are best during the long, cold, dark winter months). The 1.7 m Antarctic Submillimeter Telescope and Remote Observatory (AST/RO), located at the Amundsen-Scott South Pole Station, has been surveying the submillimeter radiation from neutral carbon atoms and carbon monoxide molecules in the interstellar medium continuously since its installation during the austral summer of 1994. In addition to making the most comprehensive submillimeter observations of the southern sky to date, the data from this pioneering instrument is greatly increasing our understanding of the role of atomic and molecular gas in the interstellar medium. After nearly a decade of observations it is becoming increasingly clear that the Antarctic Plateau is probably the prime location for submillimeter astronomy on the Earth's surface.

Simon P. Balm

See also **Amundsen-Scott Station; Astronomical Observations from Antarctica; Astronomy, Infrared; Astronomy, Neutrino; Cosmic Microwave Background Radiation**

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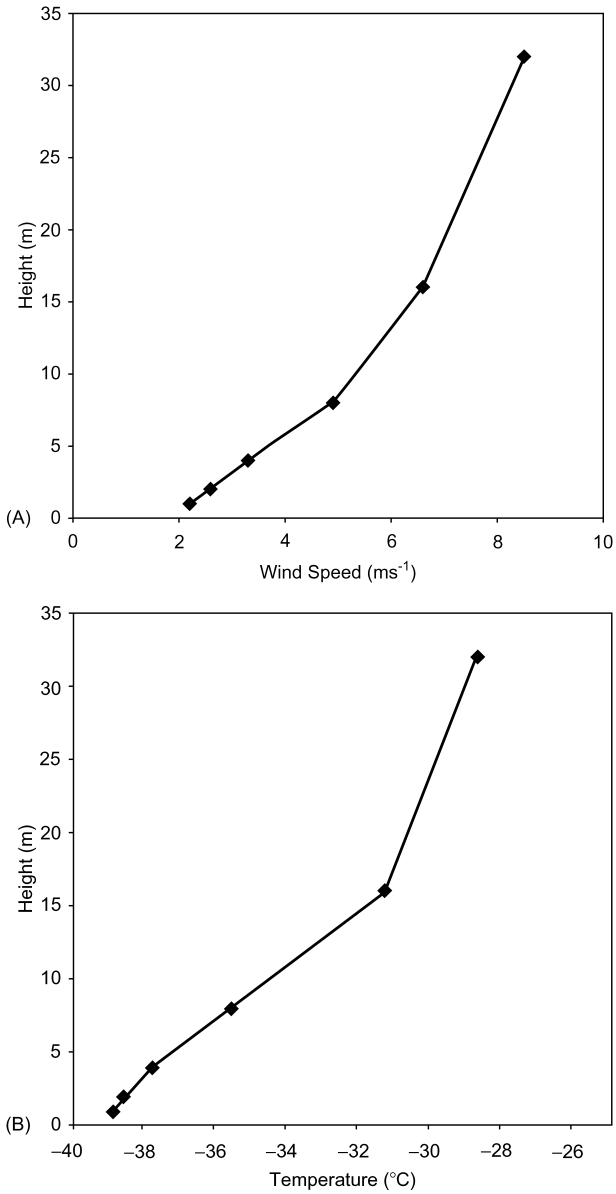
ATMOSPHERIC BOUNDARY LAYER

The atmospheric boundary layer may be defined as the part of the atmosphere that is directly influenced by the underlying surface. It is the layer through which heat, momentum, water vapour, and trace constituents are exchanged between the free atmosphere and the surface by the action of turbulence. In midlatitudes, the atmospheric boundary layer typically extends several hundred metres above the surface, whereas in the Antarctic it may be as shallow as 50 metres. The atmospheric boundary layer plays a key role in the Antarctic climate system, as it connects the atmosphere with the other main components of the climate system: ice sheets, ocean, and sea ice. Many Antarctic meteorological phenomena, such as katabatic winds and wind-borne transport of snow, are controlled by boundary-layer processes. The study of the atmospheric boundary layer in the Antarctic is thus important for the understanding of regional climate.

The structure of the atmospheric boundary layer is determined by the processes that generate and dissipate turbulence. In all boundary layers, turbulence is produced mechanically as a result of vertical variations in wind speed ("wind shear"). The rate of mechanical turbulence production depends on the wind speed and the roughness of the underlying surface. Turbulence can also be produced by convection in a boundary layer heated from below, such as when cold, continental air flows offshore over a coastal polynya. In the opposite case of a boundary layer cooled from below, as is seen over much of Antarctica during the winter, a surface temperature inversion (temperature increasing with height) develops and turbulence is damped by the stable thermal stratification (cold air underlying warmer air) of the atmosphere. Hence, both the nature of the underlying surface and the surface energy balance will affect the structure of the atmospheric boundary layer.

Convection occurs relatively rarely over the Antarctic continent. During the winter, solar heating of the surface is either absent or very small, while, even in summer, the low solar elevation and high albedo (the fraction of incident solar radiation that is

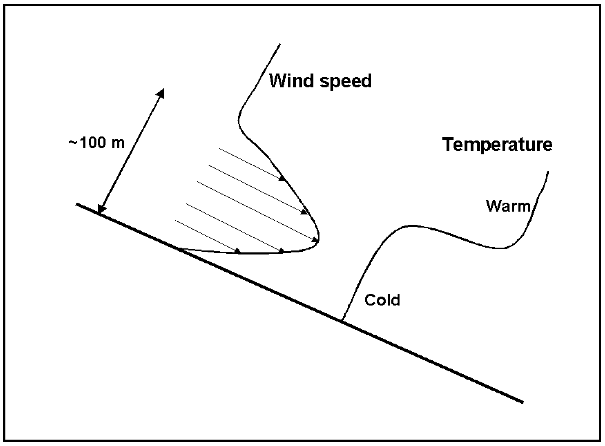


Typical vertical profiles of wind speed (A) and temperature (B) through the lower part of the atmospheric boundary layer during the Antarctic winter. (Data are from measurements made at Halley Research Station on July 7, 2003.)

reflected from the surface) of the ice sheets mean that relatively little energy is available to drive convection. The boundary layer over the continent is thus characterised by stable stratification for much of the year. The combination of stable stratification with very smooth underlying snow and ice surfaces leads to low levels of turbulence and a correspondingly shallow atmospheric boundary layer, typically between 50 and 200 m deep. Within this layer, wind speed, wind direction, and temperature vary rapidly with height. Vertical temperature gradients of more than 1°C m^{-1} are commonly seen in the lowest few metres of the boundary layer during the Antarctic winter. The strongest temperature gradients develop when wind speeds (and hence the rate of turbulent mixing) are low. At coastal locations, strong stable temperature gradients develop as the surface starts to cool after the passage of a storm. Cooling continues for, typically, 2–4 days until the next weather system brings in warm air that temporarily halts the cooling. The turbulence generated by the strong winds associated with the storm mixes the boundary layer and destroys the strong temperature gradient. Cooling resumes as the storm passes and the process repeats itself. A similar cycle may be seen in parts of the interior of Antarctica, although storms occur less frequently in this region than around the coast. Over much of the interior, however, katabatic winds (discussed later) rather than winds associated with storms are the major control on boundary layer structure.

Over sloping regions of the Antarctic ice sheets, near-surface air that has cooled becomes denser than the overlying air and will tend to flow down the local slope, generating a phenomenon known as a katabatic wind. In Antarctica, surface cooling persists for long periods and the slopes may extend for several hundred kilometres. When they blow over such distances, katabatic winds are further influenced by the Earth's rotation and, rather than blowing directly downslope, are directed between 30 and 60 degrees to the left of the fall line. Katabatic winds over the interior of Antarctica typically have speeds in the range 5–10 m s^{-1} and exhibit high directional constancy since they are strongly controlled by the local slope. In coastal regions, convergence of katabatic flows into glacial outlet valleys can generate katabatic winds of extraordinary strength, such as those encountered by Douglas Mawson's party at Cape Denison in 1912–1914 during the Australasian Antarctic Expedition.

Katabatic winds are quite shallow—often 100 m or less—as significant cooling is restricted to the shallow atmospheric boundary layer. Within this shallow layer relatively high wind speeds maintain high levels of turbulence that are very effective at mixing heat within the layer. The temperature profile through the atmospheric boundary layer in regions dominated by katabatic winds thus differs from that seen over flatter parts of Antarctica. Instead of the strong surface temperature inversion that typifies these latter regions, the katabatic boundary layer is characterised by a layer of uniform temperature extending through the shallow katabatic wind, which is capped by a layer of warmer air aloft. Within the cold katabatic layer the wind speed often exhibits a jetlike profile.



Schematic of wind and temperature profiles through a katabatic wind layer.

Because Antarctica has the form of a high dome, sloping downwards from the plateau of East Antarctica to the coast, the surface wind field is dominated by katabatic winds over a wide area. On the scale of the continent, there is a net northward transport of cold near-surface air. This is replaced by an inflow of warmer, moister air from the north, which slowly sinks into the atmospheric boundary layer. The katabatic flow thus exerts important controls on the atmospheric circulation and the heat and water budgets of the Antarctic region. Where they reach the coast, katabatic winds help to keep coastal polynyas open by driving sea ice offshore. Cooling of the open water within the polynya by the cold katabatic flow contributes to the rapid formation of sea ice in such regions.

Katabatic winds generally cease to flow when they encounter a region of negligible slope. The cessation sometimes takes the form of an abrupt "katabatic jump," where the wind speed can decrease from 10 m s^{-1} or more to near calm over a horizontal distance of less than 100 m. Strong turbulence and vertical motion accompany the jump, which is often marked by a "wall" of blowing snow and capped by small clouds. On occasions, however, katabatic winds have been observed to propagate well beyond the slopes on which they originate. Satellite imagery of the Ross Ice Shelf frequently shows warm surface signatures extending onto the flat ice shelf beyond the termini of glaciers, which drain through the Transantarctic Mountains. These signatures have been identified as continuations of the katabatic winds flowing down these valleys. Wind speeds are higher in the katabatic stream than elsewhere over the ice shelf, resulting in greater mixing and warmer surface temperatures in the region of the stream.

Boundary layer processes can affect the surface mass balance of the Antarctic ice sheets in two important ways. One way is through sublimation of snow (direct conversion of ice into water vapour) from the surface. In the cold Antarctic atmosphere, sublimation rates are generally quite small. Measurements at Halley station show that sublimation is negligible there during the winter months but can remove up to 25% of the snow falling during the warmer November to March period. The other important contribution to surface mass balance from boundary layer processes is the redistribution of snow by the wind. If the surface wind becomes strong enough (generally greater than about 7–10 m s^{-1}), snow grains become dislodged from the surface and are "lofted" by atmospheric turbulence to create a layer of blowing snow. Although few grains are lofted above 10 m, considerable amounts of snow can be transported horizontally in the shallow blowing snow layer. Where there are horizontal variations in wind speed, corresponding variations in the snow transport rate will generate regions where surface snow is eroded or deposited. In extreme cases, blowing snow transport can remove all of the snowfall from a region, leading to the formation of a blue ice field. On the scale of the Antarctic continent, the flux of blowing snow across the coastline makes a negligible contribution to the overall mass budget of the ice sheets but may locally be a significant source of fresh water in the coastal region.

The structure of the atmospheric boundary layer over the sea ice zone can be much more complex than that over the continent. An unbroken cover of sea ice insulates the atmosphere fairly effectively from the ocean, and the boundary layer that develops in such circumstances may resemble that found at continental coastal locations, with strong, stable temperature gradients. However, sea-ice cover is almost always broken by areas of open water—leads and polynyas. The sea surface temperature within such features is usually close to the freezing point, but this is still much warmer than typical air temperatures over the winter pack ice. Hence, vigorous convection develops in the atmosphere over leads and polynyas, leading to a rapid transfer of heat from ocean to atmosphere. This heating is mixed through a boundary layer that can be several hundred metres deep. As the air moves away from the lead or polynya, some of this heat remains in the atmosphere while a proportion is transferred back to the surface where it warms the surrounding sea ice. The structure of the boundary layer in the pack ice zone thus depends strongly on the fraction of the surface occupied by leads and polynyas.

The importance of boundary-layer processes in controlling Antarctic climate was recognised early in the development of Antarctic meteorology, and considerable effort has been put into studying the Antarctic atmospheric boundary layer. The prevalence of surface temperature inversions first became apparent from the pioneering upper-air measurements made by George Simpson during Robert Falcon Scott's 1910–1913 expedition. However, systematic studies of the boundary layer began with the Norwegian-British-Swedish Antarctic Expedition to Maudheim (1949–1952), and continued at several stations during the 1957–1958 International Geophysical Year. A major programme of atmospheric boundary layer measurements at Plateau station between 1965 and 1969 revealed the structure of the very stable boundary layer that develops on the East Antarctic Plateau in winter. Measurements of atmospheric turbulence require sensitive, fast-response anemometers and it was not until the development of the ultrasonic anemometer in the 1970s that such measurements became feasible in Antarctica. Since then, major atmospheric boundary layer studies, including turbulence measurements, have taken place at a number of locations, including Halley, Neumayer, Amundsen-Scott South Pole, and Dome C stations. In order to obtain the detailed vertical profiles of temperature and wind speed required by these studies, instrument packages have been mounted on a variety of lifting platforms, including small tethered balloons and kites. Acoustic remote sensing, or Sodar, has also proved to be a useful tool for studying the Antarctic boundary layer. Sound pulses fired vertically into the atmosphere are scattered by turbulent layers and can provide a qualitative (but continuous) record of the turbulent structure of the boundary layer up to 500 m. Vertical profiles of wind velocity can also be obtained by measuring the Doppler shift of the scattered sound pulses. Records from such systems reveal the complex structure of the boundary layer in the Antarctic winter. Turbulence often occurs in thin, layered structures that can persist for days at a time and wavelike motions are frequently observed propagating through these layers. The importance of these phenomena for Antarctic weather and climate is a topic of current research.

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See also **Australasian Antarctic Expedition (1911–1914); British Antarctic *(Terra Nova)* Expedition (1910–1913); Ice–Atmosphere Interaction and Near Surface Processes; International Geophysical Year; Norwegian-British-Swedish Antarctic Expedition (1949–1952); Polynyas and Leads in the Southern Ocean; Surface Energy Balance; Temperature; Wind**

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ATMOSPHERIC GAS CONCENTRATIONS FROM AIR BUBBLES

Over large parts of Antarctica, the ice sheet surface temperature does not reach the melting point, even during summer days. Ice is formed at such places by a dry sintering process. Snow crystals with their magnificent forms decay, driven mainly by temperature gradients, in a few days after deposition, into so-called firn grains. The firn is compacted by the weight of the snow cover above, first by rearrangement of the grains, and at a greater depth by the sintering process that causes the contact areas between neighboring grains to grow. Atmospheric air, filling the pore space between firn grains, is more and more driven out with the densification of the firn. A final amount of air, about 10% by volume, is enclosed in bubbles at the firn-ice transition, which occurs in Antarctica in a depth typically between 80 and 110 m below the snow surface. This air has the composition of the atmosphere at the time of enclosure. The enclosure takes place, depending on temperature and snow accumulation, typically between 200 and 5,000 years after snow deposition. Therefore, the air in bubbles is younger than the surrounding ice. By the analysis of air extracted from well-dated ice samples, the atmospheric composition in the past can be determined.

The main goals of such measurements are to reconstruct the increase of the atmospheric concentration of greenhouse gases caused by humans and possible natural variations, and to determine their causes in earlier times and their interaction with climate.

For the measurements, air has to be extracted from the ice. One method is to melt the ice and to collect the escaping air. However, for certain gases (e.g., CO_2 [carbon dioxide]), the meltwater can react with impurities and contaminate the sample. In this case, air has to be extracted by a dry-extraction method, opening the bubbles mechanically by grinding or milling the ice at low temperature. Antarctic ice just below the firn–ice transition has about 600 bubbles with a diameter of about 0.6 mm per gram of ice. However, the diameter of the bubbles shrinks with depth due to the increasing hydrostatic pressure. At a certain depth (Vostok: between 500 and 1300 m below the surface), bubbles are transformed into air hydrates. These hydrates are difficult to open mechanically, and great care is needed to avoid fractionation during extraction. The extracted air is analyzed mainly by gas chromatography, laser absorption spectroscopy, or mass spectrometry.

Measurements in different laboratories and on various ice cores from Antarctica and Greenland show that the atmospheric concentrations of the important greenhouse gases CO_2, CH_4 (methane), and N_2O (nitrous oxide) were rather stable during the first part of the past millennium but started to increase with the epoch of industrialization and accelerated growth of the global population about 200 years ago (IPCC 2001). Results from very young ice samples agree well with direct continuous measurements on atmospheric air, which, however, did not start before the second half of the past century for all three components.

Measurements on ice cores from Antarctica and Greenland also provide evidence for significant natural variations of the atmospheric concentration of the three greenhouse gases. The atmospheric CO_2 concentration shows only relatively small variations during the last glacial epoch (Indermühle et al. 2000), but with the transition from the glacial epoch to the Holocene (present warm epoch), it increased by about 76 ppmv (parts per million by volume). The increase was practically synchronous with the temperature increase, represented by the hydrogen isotope record. This synchrony between atmospheric CO_2 concentration and Antarctic temperature supports the idea that the Southern Ocean played a key role causing the increase of atmospheric CO_2 (Monnin et al. 2001). There is ample evidence that the CO_2 increase is an important amplification factor for the global temperature increase from the last glacial to the Holocene epoch. The atmospheric CH_4 concentration shows larger variations during the glacial epoch. They are synchronous with temperature variations in the Northern Hemisphere, where most of the natural CH_4 sources (wetlands) are located. The CH_4 concentration increased from about 400 ppbv (parts per billion by volume) during the last glacial maximum to about 730 ppbv at the beginning of the Holocene. The CH_4 increase had only a minor influence on the global temperature increase from the glacial to the Holocene epoch. Atmospheric CH_4 is well mixed and its concentration shows only small variations geographically. The large and rather fast variations of the concentration during the last glacial epoch are observed in all ice cores and can be used to synchronize age scales (Blunier and Brook 2001). The sources for N_2O in preindustrial times were terrestrial wetlands and the ocean. The general trend of the variations is similar to that of CH_4.

The ice core from Vostok Station allows us to extend the CO_2 and CH_4 records back to 420,000 years. It shows that the atmospheric concentration of CO_2 and CH_4 was, during this time, never as high as at present (Petit et al. 1999).

Results reported so far are based on measurements on different ice cores, and they can be considered as reliable. However, much more detailed features could be affected by artifacts due to a small enrichment or depletion of certain gas components by a fractionation during air enclosure or by chemical reactions between impurities in the ice.

A small enrichment of heavier gas molecules occurs according to the barometric formula, because air mixing in the firn layer takes place only by molecular diffusion. The effect for CO_2 in an 80 m deep firn layer at –50°C is only about 0.5 ppm (compared with an average concentration of 280 ppm).

The O_2/N_2 ratio in atmospheric air is 0.2386 at present. This ratio could have been higher during glacial epochs by about 0.0015 due to the reduced biosphere. It would be interesting to measure this effect in ice cores. However, to reconstruct this ratio with this precision seems not to be possible. Measurements on different ice cores show that O_2 is slightly depleted (Bender et al. 1995). It is assumed that a fractionation between O_2 and N_2 occurs either at the enclosure of air in bubbles or during a possible minor gas loss during storage of ice cores.

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See also **Air Hydrates in Ice; Carbon Cycle; Firn Compaction; Ice Ages; Ice Chemistry; Ice Core Analysis and Dating Techniques; Isotopes in Ice; Paleoclimatology; Pollution Level Detection from Antarctic Snow and Ice; Snow Chemistry; Snow Post-Depositional Processes**

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AUCKLAND ISLANDS

Located 460 km south of the South Island of New Zealand, the Auckland Islands group comprises the main Auckland Island (50,990 ha), five other islands—of which Adams Island and Enderby Island are the largest—and many islets, with a total area of 62,564 ha. Rising to 705 m, the islands are the remains of two coalescing shield volcanoes formed between 25 million and 10 Ma, centred respectively around Musgrave Peninsula in Carnley Harbour and Disappointment Island. Coastal erosion has removed much of the western sector of the volcanoes, forming a line of cliffs up to 400 m high. Pleistocene-age glaciers have carved the eastern coast into a series of fiords, along with cirques, U-shaped valleys, and moraine-dammed lakes. Cloudy, windy and wet weather predominates.

The mean annual temperature is 8°C, with an annual rainfall of 1000–1500 mm and light winter snowfalls. Peat soils, up to 8 m thick, are widespread. The vascular flora consists of 233 species (84% indigenous), of which five are endemic. A coastal fringing forest to 50 m altitude is dominated by the southern rata *Metrosideros umbellata,* accompanied in sheltered places by the world's southernmost tree fern, *Cyathea smithii,* and the tree fuchsia, *Fuchsia excorticata.* Upslope, this grades into shrubland of *Dracophyllum, Coprosma, Myrsine, Ozothamnus, Pseudopanax,* and *Hebe,* replaced above 300 m by grassland dominated by *Chionochloa antarctica,* interspersed with megaherbs including three species of *Pleurophyllum,* and giving way around 500 m to fellfield of bryophytes, mosses, lichens, and sedges.

The islands are the principal breeding ground of the New Zealand (Hooker's) sea lion *(Phocarctos hookeri),* one of the world's rarest seals (population 12,000–16,000). Southern elephant seals breed in small numbers, and leopard seals are occasional visitors. The islands are the main breeding ground in the southwest Pacific for a population of about 1,000 southern right whales.

The three outstanding seabirds are Gibson's albatross *(Diomedia gibsoni)* (6,000 pairs, mainly on Adams Island), southern royal albatross, and white-capped albatross *(Thalassarche steadi)* (65,000 pairs on Disappointment Island). The yellow-eyed penguin is the most conspicuous of the three penguin species breeding, and the endemic Auckland Island shag *(Leucocarbo colensoi)* (about 1,000 pairs) is prominent. Among the smaller seabirds breeding are terns, petrels, and prions. There are seventy-six species of land birds (forty-six breeding), of which six are endemic: the flightless teal *Anas aucklandica aucklandica,* the rail *Rallis pectoralis muelleri* (rediscovered on Adams I. in 1989), the rare banded dotterel *Charadrius bicinctus exilis,* the snipe *Coenocorypha aucklandica aucklandica,* the pipit *Anthus novaeseelandiae auklandicus,* and the tomtit *Petroica macrocephala marrineri.*

Some 180 insect species are recorded, one-third of which are endemic. Since 1987, goats and rabbits have been eradicated, and mice have been eradicated from Enderby Island, while pigs and cats are currently targeted for eradication.

Maori may have briefly occupied the Auckland Islands 700 years ago and were transient settlers in the mid-nineteenth century. European sealers discovered the islands in 1807 and seals were eliminated by the 1830s. American, French, and British exploring expeditions visited in 1840. An ill-fated British colonial shore-whaling enterprise existed from 1849 to 1852, and a German astronomical base was established in 1874 to observe the transit of Venus. At least eight ships were wrecked on the islands between 1864 and 1907, with the loss of more than 100 lives. Supply depots and boats were provided for castaways until 1929. There were several unsuccessful attempts at pastoral farming prior to 1910. Two coastwatching stations were occupied from 1941 to 1945. Since then, there have been sporadic scientific and conservation expeditions, and small numbers of seaborne tourists visit selected sites each year under strict controls. The islands are a nature reserve and World Heritage site. A 484,000-ha marine reserve surrounds the islands to 12 nautical miles (22 km), prohibiting the taking of fish or other marine species for commercial or recreational purposes.

Paul Dingwall

See also **Albatrosses: Overview; Leopard Seal; Penguins:**

Overview; Royal Albatross; Sealing, History of; Southern Elephant Seal; Southern Right Whale; Terns: Overview

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AURORA

The Aurora Australis is a luminous glow in the night sky of the Southern Hemisphere, most commonly in the polar region over Antarctica. It has a great variability in brightness, from a feeble glow to a brilliant display of many colours. And it can transform from quiet arcs stretching from horizon to horizon to a sky filled with spectacular dancing rays and bands. It is analogous to the Aurora Borealis in the Northern Hemisphere.

The existence of these "southern lights" was first suggested in Europe in 1733 by de Mairan, in the first textbook published that was devoted to the aurora. They were confirmed by Captain James Cook, who observed the phenomenon during his voyage of discovery to Australia in *Endeavor* in 1770. During his subsequent expedition to the Antarctic in *Resolution* (1772–1775), he and his crew had several sightings. He then coined the term Aurora Australis, and compared its colours and motions to those of the Aurora Borealis that they had viewed over Sweden. Subsequent voyages of Antarctic exploration pushed farther south and reports of auroras became common in ship's logs—such as in 1831 from John Biscoe, captain of the ship *Tula,* when surrounded by icebergs at the Antarctic Circle:

> At the same time, nearly the whole night the Aurora Australis showed the most brilliant appearance, at times rolling itself over our heads in a beautiful column, then as suddenly forming itself as the unrolled fringe of a curtain, and again suddenly shooting to the form of a serpent and at times appearing not many yards above us; it was decidedly transacted in our own atmosphere, and was without exception the grandest phenomenon of nature of its kind I have ever witnessed.

The Aurora Australis occurs well to the south of inhabited regions and only very major ones expand equatorward sufficiently to be seen over such continents as Australia (and there only a very few times a year). One of the earliest reported from Australia was by Francis Abbott in Hobart, Tasmania:

> On August 29, 1859 there appeared a most brilliant Aurora Australis extending from the W. through the S. to the Eastern part of the horizon in one continued arc of about 190 degrees and shooting up to the zenith.... The phenomenon had for thirty minutes a most magnificent appearance, the bands [i.e., rays] being in complete repose formed a truncated cone of glory, the apex of which, if projected, would have terminated in the zenith....
>
> A second display of the Aurora appeared on the night of 2nd September following, equally brilliant and extensive, but less transitory, and with this difference, that from Sunset the whole of the southern sky was of deep ruby colour....
>
> From 12 to 1 o'clock on the morning of the 3rd the Aurora broke out into flickering streamers and coruscations, as brilliant, and with as much diversity of colour as on the 29th of August, forming in the zenith a well defined corona, which shortly after became diffused and then dispersed....

These two auroras were also seen in North America, Jamaica, Rome, and Athens and are on the list of historical great auroras. The latter one was also viewed and sketched from Melbourne.

Many countries sent expeditions to the Antarctic in the early part of the twentieth century. One was the British National Antarctic Expedition of 1901–1904. On this, Robert Falcon Scott and his party were forced to establish winter quarters on Ross Island, near McMurdo Sound. Many sightings of auroras were made from there. Douglas Mawson, a member of Ernest Shackleton's British Antarctic Expedition of 1907–1909, recorded very detailed observations of the aurora. He continued these scientific studies during his 1911–1914 Australasian Antarctic Expedition.

The geographical distribution of the aurora in the Southern Hemisphere was first reported by Boller in 1898, based on some 780 nights during which auroras were observed. There were several later efforts to map the southern auroral zone but it was not until the International Geophysical Year (IGY) during 1957–1958 that more observational data allowed Feldstein to produce much improved maps of both auroral zones. His southern map showed that this auroral zone roughly encircled Antarctica, well poleward of the southern continents, and that the percentage of nights that one would expect to see overhead auroras in major capital cities was very low (Hobart, 3; Sydney or Auckland, 1; Capetown, 0.5; Buenos Aires, .01). It is not surprising that observations and studies of the Aurora Australis in early times were scanty, compared with the much more extensive studies of the Aurora Borealis, which in contrast occurred over many populated areas.

The Aurora Australis generated several legends and beliefs among early natives of Australia and New Zealand, even though it occurred usually well to the south of them and perhaps was not an integral part of their culture. The auroras they saw were usually red, so they quite naturally associated them with glowing fires. The Maori of New Zealand believed that some of their ancestors had journeyed far south by canoe and become trapped in ice. Their descendants in that inhospitable zone sometimes lit huge bonfires signaling their kinsmen in hope of being rescued. Thus, the Tahu-nui-a-Rangi (Great Glowing of the Sky) was a reflection of these great fires in the night sky.

Certain aboriginal people in Northern Australia viewed the aurora as the feast fires of the Oolapikka folk—ghostly beings who sometimes spoke to the people through these auroral flames. Only the elders dared look at the lights and interpret their messages. Those in the south explained auroras as the campfires of spirits, flickering over Kangaroo Island off the south coast of Australia. Among the Kurnai people of southeast Australia the aurora needed no interpretation: it was an unequivocal and terrifying warning from the Mungan Ngour, the "Great Man," and a sign of his wrath. The Kurnai would run about trying to fend it off, and shouting at it to go away.

It had been long recognized that the southern and northern lights had some similarity and that the magnetic field of the Earth exerted some influence over them. There was some evidence that auroral displays occurred simultaneously in both hemispheres. A literature study about 1865 revealed that of thirty-four displays seen in the Southern Hemisphere, twenty-three were coincident with auroras reported in North America. Photographs taken in 1968 from coordinated aircraft flying over Alaska and south of New Zealand showed auroras that were near mirror images of each other. More detailed studies with spacecraft imagers have since established that the two auroras are conjugate (occurring on both ends of the same magnetic field line). Comparisons of such joint images show some small differences in detail (intensities and form), explained as due to irregularities in the geomagnetic field. So, the southern and northern lights can be considered integral parts of a global phenomenon. Comments that follow can therefore apply equally to either the southern or the northern lights.

As for general characteristics, the aurora varies in brightness from a faint glow at quiet times to a brightness approaching that of the full moon during active periods. It is a permanent optical feature of the upper atmosphere, appearing in each hemisphere as an oval about 100 km or more above the earth. Its position varies with geomagnetic activity. During moderate activity the aurora is located about 23 degrees from each magnetic pole on the night side of the Earth and about 15 degrees on the dayside. During magnetically quiet times the oval shrinks poleward by as much as 5 degrees, significantly reducing the size of the polar cap, that region poleward of the aurora. The South Magnetic Pole is near Vostok Station, Antarctica, and the southern "auroral oval," the zone of most frequent auroral occurrence, roughly encircles the Antarctic Continent. It is only during very major disturbances that the southern lights move sufficiently equatorward to be seen over continents such as Australia.

While spectacular auroral displays have been recorded through history as far back as 500 BC, it has been through concerted international efforts, such as the IGY, and succeeding *in situ* balloon, rocket, and satellite investigations that most understanding of the phenomenon has emerged. The aurora is caused by particles, mainly electrons, bombarding the upper atmosphere gases. Its visible spectrum consists mainly of emissions from excited oxygen atoms (green and red emissions) and nitrogen molecules (violet and pink). The variation in colour seen in different displays is due to differing depths of penetration into the atmosphere by the bombarding electrons.

The emission spectrum extends over a wide frequency range extending from x-rays to radio emissions. Some major emissions are in the extreme ultraviolet region and are absorbed by the atmosphere, but can be detected from above by spacecraft imagers. Orbiting satellites such as the Dynamics Explorer, Viking, Polar, and Image have been used routinely since 1981 to photograph the aurora globally, even in the presence of full sunlight. They have verified that the aurora is a permanent optical feature, consisting of two full haloes encircling the earth. Viewed around this "24-hour oval" there are typically quiet arcs in the evening sector, dynamic brighter auroras in the midnight sector, diffuse auroral remnants in the morning sector and faint, red aurora through the noon sector.

The IGY prompted the establishment of many Antarctic bases in the 1950s, many of which have had active research programs, including auroral studies. At the Australian Mawson station and the Japanese Syowa station, aurora can be seen on practically every clear night. They are about 25 degrees from the South Magnetic Pole. Amundsen-Scott South Pole Station, established in 1956, is just poleward of the center of the auroral zone, but an ideal location for studies of auroras near midday—aided by several months of 24-hour darkness each year.

The period 1996–2003 went from solar minimum (~1996) to solar maximum (~2002) and the observations and photographs of Robert Schwarz, a scientist then at Amundsen-Scott Station, illustrate how auroral activity and poleward expansion increase with solar activity during the 11-year sunspot cycle. They are in agreement with the more extensive evidence from the Northern Hemisphere.

Auroral activity is controlled to a major degree by solar activity and the solar wind, that continuous stream of electrons and protons emanating from the sun. Major auroras are due to coronal mass ejections (CMEs) from the sun, while auroral substorms are usually triggered by changes in the solar wind. Auroral substorms occur periodically and typically last for about 3 hours. The first sign is a sudden brightening of the quiet auroral arc in the midnight sector. This brightening spreads westward along the auroral oval, then the aurora expands poleward (termed the expansive phase). During this time the aurora is most active and colourful, with draperies, transient rays, and rapidly moving arcs. The aurora then fades and recedes to lower latitudes and is replaced by fainter patches, often pulsating. This recovery phase lasts for up to 2 hours.

Great auroras expanding down to low latitudes and lasting up to 2 days occur very occasionally, and have been marvelled at through the ages. They are marked by their near global extent, their long duration, their brightness, and their vivid colour. As they expand to lower latitudes they usually exhibit a deep red colour. Global power inputs via particle precipitation have been estimated as high as 1000 gigawatts during the peak of such auroras. They tend to occur around or following the peak of the 11-year cycle of solar sunspot activity (but can occur any time). While there may be something special causing these very unusual auroras, so far it appears they are just "bigger" than the usual substorms and not greatly different.

One of the great auroras of the past century occurred on March 13–14, 1989, with sightings reported from Argentina, Britain, and much of North America. Satellites recorded images of greatly expanded auroras over both southern and northern latitudes. That aurora lasted more than 30 hours and caused a major power disruption along the American eastern seaboard. Another aurora approaching the same magnitude was on April 6–7, 2000. The bright red glow lasted for three hours in South Africa, north of Capetown. It was also viewed over much of Europe and throughout North America.

One last example was the great Aurora Australis seen on March 30–31, 2001. As reported in detail by the Royal Astronomical Society of New Zealand, it was visible over much of New Zealand and Southern Australia through the whole night and was often red in colour. There were Aurora Borealis sightings at the same time over much of North America and across Norway.

It is noteworthy that for the latter two auroras there was a full array of spacecraft in orbit and it was possible to trace their full evolution from beginning to end. The spacecraft SOHO (for Solar and Heliospheric Observatory) observed the solar CMEs, which caused them. The progress of the clouds and the solar wind streaming earthward were monitored by the ACE (for Advanced Composition Explorer) and WIND satellites, and the auroras resulting some 2–3 days later (the sun-earth transit time) were recorded by several satellites.

It is difficult to get auroral observations from the ground in both hemispheres simultaneously, due to the asymmetry of seasons. The best opportunities are around the equinoxes, when there are similar day and night conditions in both auroral zones. Fortunately, auroral activity is somewhat greater through the spring and autumn seasons due to increased magnetic activity, which adds to the chances of joint observations. Major displays of Aurora Australis were reported by viewers in New Zealand and Australia on May 4, 1998, October 24 and November 4, 2001, October 23, 2003, and November 7, 2004.

Poleward of the auroral zones there are often auroras, referred to as "polar auroras." They were first noted by early Antarctic (and Arctic) explorers. They are of similar origin to lower latitude auroras but are somewhat different in appearance and character. They occur under quiet magnetic conditions when auroral oval activity is minimal. They consist of very narrow arcs, usually faint and colourless, and they are always aligned along the Sun-Earth line. They usually are seen to split off the poleward edge of the auroral oval and drift across the polar cap, or to linger for hours depending on the state of the solar wind.

There is now a general understanding of auroral phenomena, but some questions still remain and these are now being addressed by several countries in ongoing research on the Aurora Australis in Antarctica, at over twenty stations located around the continent. This work has been recently extended with the addition of several remote automated geophysical observatories on the continent, and with an array of auroral radars that cover much of the southern auroral zone. So, while historically much of the knowledge about auroras came from observations of the Aurora Borealis, the Aurora Australis has captured its proper share of attention during the past half-century with the establishment and operation of the Antarctic research bases.

DONALD J. MCEWEN

See also **Antarctic: Definitions and Boundaries; Auroral Substorm; Australasian Antarctic Expedition (1911–1914); Biscoe, John; British Antarctic *(Nimrod)* Expedition (1907–1909); British National Antarctic *(Discovery)* Expedition (1901–1904); Cook, James; Geomagnetic Field; International Geophysical Year; Mawson, Douglas; Ross Island; Scott, Robert Falcon; Shackleton, Ernest; Solar Wind; South Pole; Vostok Station**

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AURORAL SUBSTORM

A repeatable large-scale brightening of the aurora on the nightside of the Earth at polar latitudes, the auroral substorm was identified and defined in 1964 by Japanese scientist S. -I. Akasofu from all-sky camera movies of the aurora taken during the International Geophysical Year 1957–1958. The substorm takes its name from the magnetic storm, of which it was thought to be an integral part. However, it is now uncertain whether this is true since a magnetic storm can occur in the absence of substorms, and vice versa.

The auroral substorm begins with substorm onset when a discrete auroral arc brightens near the equatorward edge of a preexisting latitudinal band of discrete arcs. There follows an expansion phase in which the brightening expands eastward, westward, and poleward. This lasts 20–30 minutes until the brightening reaches its maximum poleward extent. The substorm then enters a recovery phase of 1–2 hours duration, during which the aurora fades to pre-onset levels. During the course of a substorm, about a thousand million million joules of energy are dissipated in the Earth's auroral atmosphere at about 100 km altitude, similar to the energy of a hurricane.

The location of substorm onset is roughly around midnight local time near the Arctic and Antarctic circles. More precisely, its location is ordered with respect to the geomagnetic pole and the Sun. Defining a magnetic coordinate system in which ±90° geomagnetic latitude is at the North/South Magnetic Pole and 12 hours magnetic local time (MLT) is the magnetic longitude closest to the Sun, the most common substorm onset location is 67° geomagnetic latitude and 23 MLT. As a result, Syowa is probably the most favourable Antarctic station at which to observe substorms.

The waiting time between one substorm onset and the next is quite variable. The most common waiting time is 3 hours but substorms can be separated by over a day. The average waiting time is about 6 hours and hence a ground-based observer may typically expect to see one or two auroral substorms per night, assuming there are no clouds to obscure the view of the aurora.

Since its discovery, the auroral substorm has been found to correlate with changes in many other phenomena in the near-Earth space environment, including electrical currents, the geomagnetic field, ionised particles, and electromagnetic waves. (Collectively, these signatures define the magnetospheric substorm, the magnetosphere being the comet-shaped region of near-Earth space dominated by the geomagnetic field.) It has been shown that the substorm onset follows a growth phase of typically 40–60 minute duration during which energy is slowly accumulated in the geomagnetic field before its relatively sudden release at substorm onset. This energy is extracted from a flow of ionised material from the sun called the solar wind, whenever the solar magnetic field within it is directed southward. It may thus be feasible to predict substorm onset from measurements made in the solar wind by spacecraft, but knowledge is not yet sufficiently developed to do this.

Mervyn Freeman

See also **Antarctic: Definitions and Boundaries; Aurora; Geomagnetic Field; International Geophysical Year; Ionosphere; Magnetic Storm; Magnetosphere of Earth; Solar Wind; South Pole**

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AUSTRALASIAN ANTARCTIC EXPEDITION (1911–1914)

The Australasian Antarctic Expedition (AAE) was an impressively planned and executed three-base expedition under the command of Douglas Mawson, then a lecturer in geology at the University of Adelaide, that was remarkable in both its scientific research and its geographical accomplishments. However, the achievements of the AAE were overshadowed by the disasters of Robert Falcon Scott's last expedition, and their full significance was not widely appreciated outside Australia at the time. It was an Englishman, J. Gordon Hayes, who first put them into proper perspective: "Sir Douglas Mawson's Expedition," he wrote, "judged by the magnitude both of its scale and of its achievements, was the greatest and most consummate expedition that ever sailed for Antarctica."

From the outset, the AAE was conceived by Mawson as a vast project. His hand-drawn plan of action (February 1910) shows a 2,000-mile (3200 km) arc of coast from Cape Adare west to Gaussberg in Kaiser Wilhelm II Land: all this was to be explored. There were to be three continental bases, each with teams striking east and west, and one going south as well. No expedition on this scale had ever been conceived for Antarctica.

In December 1911, the expedition left Hobart, its first stop being at Macquarie Island, where a five-man base under George F. Ainsworth was set up to serve as a meteorological station and wireless-relay point for the Antarctic bases. In the next 2 years extensive geological, biological, botanical, and survey and charting work was also done there.

In early January 1912, with the expedition ship *Aurora* unable to approach a landing site as quickly as he hoped, Mawson was forced to reduce the continental bases from three to two. Ultimately, they found a suitable site for the Main Base (or Winter Quarters, as Mawson often called it) at Cape Denison in Commonwealth Bay, Adélie Land. Mawson and seventeen other expedition members were landed here. *Aurora* then sailed 1,500 miles (2400 km) west in search of a place to land the men chosen for the Western Base. This was found on what was later named the Shackleton Ice Shelf, and, with great unease, John King Davis, second-in-command of the expedition and captain of the *Aurora,* allowed the Western Base to be set up on the ice shelf under the command of Frank Wild, whom Mawson had originally met on Ernest Shackleton's British Antarctic Expedition (as he had Davis). Under Wild's command were seven men with no previous Antarctic experience.

At Cape Denison, Mawson oversaw the construction of two prefabricated wooden huts that were joined into one and a small magnetograph hut. Unfortunately this turned out to be perhaps the windiest place on the continent, so that winter and most of spring were spent indoors on scientific work, largely biological, zoological, and meteorological. Likewise, difficult conditions for the members at the Western Base kept them in their hut most of the winter. It was not until November 1912 that the serious sledging program was able to begin and the teams set out on their journeys. A total of 2,600 miles (4200 km), out and back, were sledged over territory entirely unknown until then. This figure included, in addition to Mawson's own ill-fated journey 310 miles (500 km) to the southeast and marches by support parties, a journey of 160 miles (260 km) to the west, one of 300 miles (480 km) to the south-southeast to within 50-odd miles (80 km) of the areas of the South Magnetic Pole, and another of 270 miles (430 km) to the east, much of which was over sea ice. At the same time, from the Western Base, 800 miles (1280 km) were traversed, including a journey of more than 200 miles (320 km) west to Gaussberg, and another of around 100 miles (160 km) east to the Denman Glacier. All of this was—for journeys from both bases—frequently in the face of appalling weather. During the 91 days of Mawson's own journey, for instance, there were 43 days with winds of force 8 or stronger, 17 days with winds of force 10 and over, and seven days with winds of force 12 (80 mph or 128 kmph).

In addition to the exploratory activity, there was pioneering wireless work (including the use of wirelessed time signals to establish the fundamental longitude for Cape Denison), exploratory and oceanographical work aboard *Aurora* (under Davis), and diverse scientific work at each of the bases.

Hayes made a very telling point in distinguishing between territory *discovered* and territory *explored*—that is, charted. By this test, the Norwegian explorer Roald Amundsen—the first to the South Pole—discovered 1,300 miles (2080 km) of land and 450 miles (720 km) of shelf ice, but explored very little of it. Scott's first *(Discovery)* expedition discovered 1,050 miles (1680 km) but explored only about 200 (320 km); his second *(Terra Nova)* expedition discovered about 285 miles (460 km) of new ground but explored only 100 (160 km). And Shackleton's British Antarctic Expedition discovered 1,035 miles (1660 km) of new land and explored most of it. Hayes tabulated the results in very clear form, concluding (1928: 257):

> As [Mawson] discovered and explored so much, care has been taken not to over-estimate his results. Amundsen, owing to his skill in the use of dogs, comes next in geographical discovery alone; but his maps make accuracy very difficult, and his work was not on the same level as that of the other explorers. Mawson's result, for one expedition, is magnificent, when his scientific work is included also.

Even at the time, as the AAE was returning to Australia in February 1914, there was one man qualified to judge who summed things up correctly—W. S. Bruce, leader of the Scottish National Antarctic Expedition of 1902–1904. "It is not too much to say," Bruce wrote Mawson, "without any intention to flatter, that your expedition has been the most successful of any recent Antarctic expedition. As a scientific man you have trusted your own powers to conduct the expedition entirely on scientific lines without seeking to secure popular éclat by proposing a sensational advance of an athletic kind" (Bruce 1914).

The great value of the AAE, then, consisted in the extent of its geographical exploration and the quality of its scientific leadership. Unlike Shackleton's and Scott's expeditions, it always put science first, the scientific ideal embodied in the commander, an academic and field geologist. In preparing for it, Mawson relied on support from private sources, from Federal and State Governments, and from the Australasian Association for the Advancement of Science (AAAS), of which Mawson was a member. Essentially, however, it was a private expedition. The scientific personnel were chosen by Mawson (theoretically the AAAS had a watching brief on this), and all the preparations were in his hands. It was his affair. He organised the funding, selected the men, the ship, and the equipment, and there was no one to nay-say him. The avant garde nature of Mawson's AAE is most epitomised in two things. First, he was the initial man to take an airplane to the Antarctic, and, indeed, it was the most advanced form of airplane of that period, a monoplane: a French REP (after its owner-developer, Robert Esnault-Pelterie), notable for its tapered, tubular-steel fuselages, generally triangular in section but lozenge-shaped on the latest D-type that Mawson chose. There was also a single control for pitch and roll, an advanced feature. The five-cylinder engine was fan-shaped. With ski undercarriage, the cost was £955 4s 8*d*. The extremely windy conditions at Cape Denison prevented its being flown there, and instead it was used (briefly) as an "air-tractor," dragging supplies. Prior to being taken south it was test-flown (crashed and repaired) in Adelaide in 1911 as a publicity stunt to raise funds for the AAE. Mawson was also the first explorer to take colour photography to the Antarctic—Lumière Autochrome plates, 400 of them, many preserved today in the Mawson Antarctic Collection in the South Australian Museum, Adelaide. Mawson selected and purchased the cameras for the expedition (with the latest German Zeiss Tessar lenses, also a Busch telephoto lens), and appointed Frank Hurley as the expedition's photographer. Hurley was a more imaginative and daring photographer than Scott's, Herbert Ponting. Hurley's work on Shackleton's Imperial Trans-Antarctic Expedition (1914–1917), including flash photography of the breakup of *Endurance* at night, is justly famous, but his glass-plate photographs (including stereos and Autochromes) of the AAE are equally fine and dramatic. Like the photographic materials, all the scientific equipment on the AAE was the very best. Some was loaned by the Prince of Monaco, an oceanographer of international repute. Other pieces were supplied by Negretti and Zambra, and some were loaned by the Admiralty and the Royal Geographical Society. The wireless equipment was produced by Telefunken.

In addition to its geographical and scientific aspects, the AAE undoubtedly had an unspoken strategic dimension. The Australian government contributed £10,000 for a reason. Discovery implies ownership. Australia is an isolated outpost of European civilisation between East Asia and Oceania. Its strategic approaches are the oceans that surround it. The Russians and Germans had long since shown an interest in Antarctica. Neither was necessarily friendly to the British, and Australians were, at that time, British. It made sense for the Australian government to contribute to the funding of an expedition that promised to chart and claim for Australia, as part of the British Empire, a vast arc of Antarctica directly to the south and southwest of the Australian continent. Mawson's Antarctic expeditions of 1929–1931 were more overtly imperial, and as a result of these expeditions and the AAE, Australia claimed fully 40% of the Antarctic continent as its own.

Although there were seven major sledging parties (not including the depot or support parties), the event for which the AAE is best known was Mawson's heroic month-long survival trek. On November 10, 1912, he set out from the Main Base with two young companions, Dr. Xavier Mertz (a Swiss prize-winning skier) and Lieutenant Belgrave Ninnis, heading southeast and then east, across the Mertz and Ninnis glaciers and the plateau of George V Land. A month out, 311 miles from Main Base, Ninnis fell hundreds of feet down a crevasse (deceptively covered by a snow bridge) with his dogs and sledge, which carried practically all their food, the main tent, Mertz's warm Burberry trousers and helmet, their eating utensils, sledge mast, sail, and other materials. Mawson and Mertz were left with their sleeping bags, 10 days' supply of food, a spare tent without poles, their private bags, and a cooker and kerosene. Their dogs were in poor condition and there was nothing to feed them except each other. "We considered it a possibility to get through to Winter Quarters by eating dogs," Mawson wrote in his sledging diary, "so 9 hours after the accident started back, but terribly handicapped.... May God help us."

What followed was a wild dash across the plateau of King George V Land, including the upper reaches of the Ninnis and Mertz glaciers. They travelled by night, the Sun low down and the crisper surface offering less resistance to the sledge. Across ice fields ribbed with slippery sastrugi, dog after dog gave out and was shot. More than half the way back Mertz sickened, delaying progress, and after a few days he died. It was not until February 8 that Mawson finally reached Main Base, by which time *Aurora* had come, picked up most of the men, and—only hours before—sailed off to collect those at Western Base. A small party had remained behind at Main Base to await Mawson's return, and with these he spent the rest of 1913 in Antarctica, continuing to make scientific observations and, eventually, carrying out a small sledging programme. The next summer, after great difficulty in raising the financing for a relief voyage south, Davis and *Aurora* picked up the men still at the Main Base and, following yet more exploratory and oceanographic work, arrived back in Australia in late February 1914.

The scientific results of the AAE were published in a long series of *AAE Scientific Reports,* authored by Mawson and others (he farmed them out to specialists all over the world). His published account of the expedition, in two volumes, *The Home of the Blizzard,* appeared in London in 1915. It is thorough and well written (Mawson was assisted by one of his expedition members, Dr. Archibald McLean, who heavily worked over the drafts). There are numerous photographic plates, and the entire work reflects the scientific spirit that infused the AAE from its inception.

PHILIP AYRES

See also **Amundsen, Roald; Antarctic: Definitions and Boundaries; British Antarctic *(Nimrod)* Expedition (1907–1909); British Antarctic *(Terra Nova)* Expedition (1910–1913); British National Antarctic *(Discovery)* Expedition (1901–1904); Bruce, William Speirs; David, T.W. Edgeworth; Davis, John King; History of Antarctic Science; Imperial Trans-Antarctic Expedition (1914–1917); Macquarie Island; Mawson, Douglas; Photography, History of in the Antarctic; Scott, Robert Falcon**

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AUSTRALIA: ANTARCTIC PROGRAM

After some 150 years acting as stepping off or returning point for expeditions representing many nations (Wilkes, Ross, Dumont d'Urville, Borchgrevinck, Amundsen, Mawson, and Ellsworth), Australia established its own continuing, government-funded program with stations on Heard Island and Macquarie Island late in 1947. The closure of Heard Island late in 1954 permitted resources to be allocated to building Mawson Base on the Antarctic mainland early in 1954; Mawson has been occupied continuously since and is the longest continuously occupied station on the mainland of Antarctica.

At the outset, a decision was made to have the core of the Australian program—the Australian National Antarctic Research Expeditions (ANARE)—conducted by a government institution that would have dual functions of support and research. After belonging to many different federal government departments, this institution—the Australian Antarctic Division (AAD)—now resides in the Department of Environment and Heritage. Scientific activities in the AAD were to be conducted in disciplines not covered by other government organisations; thus the AAD conducts programs in biology (terrestrial and marine), glaciology, upper atmosphere and cosmic ray physics, human impacts, and polar medicine. These subjects are aided by a technical support group. Earth sciences originally were to be conducted by the Bureau of Mineral Resources (now Geoscience Australia), meteorology by the Bureau of Meteorology, and ionospheric studies by the Ionospheric Prediction Service. A major development since the AAD moved to Tasmania early in 1981 has been the increasing role of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) both in cooperation directly with the AAD or through its involvement in cooperative research centres. The government program was, and still is, supplemented to a large extent by projects conducted in all disciplines in most Australian universities, particularly the University of Tasmania, which has established the Institute of Antarctic and Southern Ocean Studies (IASOS). The AAD makes available grant money in support of researchers from outside government agencies.

Internationally, the Australian program has been a significant participant in the Scientific Committee on Antarctic Research (SCAR) and its instruments in both management and scientific cooperation. With the advent of Antarctic Treaty instruments such as the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR), which was signed in, and has its headquarters in, Hobart, and the Protocol on Environmental Protection to the Antarctic Treaty the research program has evolved to meet new requirements specific to these agreements.

Currently, the program operates from three permanent continental stations—Mawson (67°36′ S, 62°52′ E: 1954–present), Davis (68°36′ S, 77°58′ E: 1957–present, excepting 1965–1969) and Casey (66°18′ S, 110°32′ E: 1969–present). Casey was at first the United States station of Wilkes established for the International Geophysical Year but assumed by the Australian program in 1969; it has been moved twice to ever newer sites. All have year-round scientific programs. In addition there is a permanent station on Macquarie Island (54°30′ S, 158°5′ E; 1947–present), which is part of the state of Tasmania. Provisions also exist for operation of summer programs at Heard Island (initially at Atlas Cove; 53°01′ S, 73°23′ E), Larsemann Hills (Law Base), Bunger Hills (Edgeworth David Base), and Prince Charles Mountains. In addition to the land-based program, a diverse marine science research program in biology, sea-ice studies, and oceanography is conducted from FRV *Aurora Australis* and the earth sciences from *Aurora Australis* supplemented by use of other vessels, either nationally or in concert with other nations.

Observatory functions are an important component of the program and all stations have meteorology observatories. All stations have some combination of seismological and magnetic observations and Mawson is one of the primary sites for monitoring in support of the Nuclear Non-Proliferation Treaty.

The headquarters of the program was initially at a variety of sites in Melbourne, Victoria, but a government decision led to the move from Melbourne to Kingston, Tasmania. The new headquarters were opened in April 1981 by HRH Prince Charles. There are now over 300 staff in the AAD. Annual budget for 2000/2001 for the AAD alone was AU$98.94 million.

At first, all transport between Australia and Antarctica depended on chartering of foreign vessels, in particular the Danish MV *Kista Dan, Magga Dan, Thala Dan,* and *Nella Dan.* In the 1980s, following the loss of MV *Nella Dan* off Macquarie Island, the government decided to build, in Australia, an icebreaking research and supply vessel—FRV *Aurora Australis*. This has been in service since 1990. It was supplemented for many years by the German cargo ship MV *Icebird* (now *Polar Bird*). In the 1960s, the AAD was served by fixed wing aircraft but this ceased after losses. After detailed study, it was decided to resume air transport, and fixed wing aircraft began flying within Antarctica in the 2004–2005 austral summer. During 2005, the government made finance available to fly routinely from Australia to a compressed-snow runway at Casey. Initial experimental flights are scheduled for the 2005–2006 summer. It is expected that this will increase flexibility and allow improved servicing of distant field sites in Antarctica.

The goals of the program vary in line with government policy and at present the four goals are to:

- Maintain the Antarctic Treaty and to enhance Australia's role in it;
- Protect the Antarctic environment;
- Understand the role of Antarctica in the global climate system; and
- Undertake scientific work of practical, economic and national significance.

To achieve these ends the AAD program is organised into a series of branches:

- Directorship,
- Science,
- Operations,
- Policy coordination,
- Polar medicine, and
- Corporate.

In 1990, the Australian government instituted a Cooperative Research Centres program and one of these, at the University of Tasmania, was dedicated to research into Antarctic and Southern Ocean Climates. A new Cooperative Research Centre into Antarctic Climate and Environment (CRC-ACE) followed, also in Hobart.

The Australian Antarctic program has been a major contributor to Antarctic scientific literature and in recent years there have been symposia to consolidate knowledge of particular areas.

Major scientific achievements in recent years have included the move into all areas of marine science (especially since 1981), glaciology traverses into the hinterland between Mawson and Davis and ice coring near Casey, establishment of a LIDAR (for "light detection and ranging") facility at Davis, modernisation of the observatory functions as part of a redevelopment of the station buildings, major inland earth science studies in the Prince Charles Mountains and in the Vestfold Hills, environmental research designed to rectify past damage and to improve operational environmental care, and recognition that the region is a leading source of information on the evolution of the Antarctic environment over the last 200 million years, including the drilling of four legs of the Ocean Drilling Program (ODP).

Planning is now active for involvement in the International Polar Year of 2007/2008, including a leading role in the Census of Antarctic Marine Life (CAML).

Patrick G. Quilty

See also **ANARE/Australian Antarctic Division; Antarctic Treaty System; Australasian Antarctic Expedition (1911–1914); British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); British Antarctic (*Southern Cross*) Expedition (1898–1900); Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Ellsworth, Lincoln; French Naval (*Astrolabe* and *Zélée*) Expedition (1837–1840); Heard Island and McDonald Islands; International Geophysical Year; Macquarie Island; Mawson, Douglas; Norwegian (*Fram*) Expedition (1910–1912); Protocol on Environmental Protection to the Antarctic Treaty; Scientific Committee on Antarctic Research (SCAR); United States Exploring Expedition (1838–1842)**

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AVIATION, HISTORY OF

For the first time in history, new land was being discovered from the air, declared Sir Hubert Wilkins in 1929 on his return from a flight that turned a key to unlock the exploration of Antarctica in the twentieth century.

Even as Amundsen, Scott, Shackleton, and Mawson struggled to reach their polar goals, in another part of the world an air age had dawned. But almost two decades would pass before the Wilkins-Hearst Expedition's slim Lockheed Vega in a take-off from a volcanic airstrip on Deception Island signalled a most dramatic change in humankind's striving to lift the veil of the last unknown continent.

In an age of ponies, dogs, and man-hauled sledges, the old explorers would be content with maybe 20 miles a day, maybe 10 or less. Tramping a cruel, snow-crusted surface would cost them in starvation, isolation, tragedy. The new explorers spoke in terms of hundreds of miles a day, if not thousands;

starvation and isolation were mostly put behind them, but regrettably, not always the tragedy.

The full implication of the airplane to Antarctic exploration was little realised when Captain Robert Falcon Scott, in a balloon named *Eva,* rose above the Great Ice Barrier on February 4, 1902. The German explorer Erich von Drygalski followed with a balloon flight from the ice of Kaiser Wilhelm II Land, a few months later, drawing on advanced technology, Drygalski was able to talk from his balloon by telephone to the crew watching anxiously below.

The Australian explorer Douglas Mawson planned to include a heavier than air machine in his Australasian Antarctic Expedition of 1911. But the Vickers REP monoplane broke its fragile wings and in the reduced role of an "air tractor" enjoyed short-lived service before succumbing to the cold of Commonwealth Bay.

Pioneering the Antarctic skies would be left to another man from South Australia, Sir Hubert Wilkins, who had already won fame on the battlefields of World War I and in Arctic aviation. Though a pilot himself, Wilkins preferred to have the seasoned polar aviator Carl Ben Eilson at the controls when the Wilkins-Hearst Expedition reached the Antarctic Peninsula in 1928. Their two Lockheed Vega highwing aircraft, *San Francisco* and *Los Angeles,* acknowledged the generosity of William Randolph Hearst, the Californian press magnate who financed their exploits.

In *San Francisco,* Wilkins and Eilson made a brief yet historic test flight on November 26, 1928, from a rough volcanic scree strip they had scraped alongside the whaling station at Deception Island. The following month was spent in further test flights, including one in which *Los Angeles* suffered wing damage when it broke through the ice, leaving them with one fit aircraft. Wilkins and Eilson knew they must take a chance. Five days before Christmas, in *San Francisco,* they went aloft on a course of 1,000 miles across the Antarctic Peninsula, photographing, sketching, and gazing in wonder—and at the end of 10 hours were back on Deception Island, in time for a dinner where they toasted the new age of air exploration.

Commander Richard E. Byrd, USN, led the United States to dominance of the Antarctic skies, beginning with his first expedition in 1929. From Little America I, located on the Bay of Wales at the far eastern edge of the Great Ice Barrier (Ross Ice Shelf), he operated three aircraft—a Ford trimotor for long distance missions, supported by a Fokker, the *Virginian,* and a Fairchild, *Stars and Stripes*. On November 28, 1929, the Ford trimotor *Floyd Bennett,* piloted by Bernt Balchen, achieved Byrd's goal of first flight to the geographic South Pole, covering 1,750 miles and completing the historic and hazardous return journey in 17 hours 28 minutes. Byrd, now promoted to Rear Admiral (retired) placed more emphasis on photomapping when his second expedition resumed operations at Little America II in December 1933. *William Horlick,* a Curtis Wright Condor biplane, was the largest of the four aircraft; the other three were a Fokker, *Blue Blade,* and a small Fairchild, *Miss American Airways,* both high wing monoplanes, and a Kellett K-4 autogiro, the first rotary wing machine taken to Antarctica. The latest still and movie cameras were among his equipment, as was short wave radio that (being a superb publicist) he used in weekly broadcasts to American households.

Inspired, maybe, by Admiral Byrd's exploits, a New York adventurer-millionaire, Lincoln Ellsworth, made three attempts to fly across Antarctica, beginning in 1934. With Sir Hubert Wilkins as his manager and, initially, with Bernt Balchen as chief pilot, Ellsworth chose a sleek Northrop Gamma 28 all-metal low wing monoplane named *Polar Star* to make the crossing, starting from a base on the Antarctic Peninsula. By the time of his third expedition, a Canadian, Herbert Hollick-Kenyon, was the replacement pilot, while Wilkins stood by with Ellsworth's ship, *Wyatt Earp.* From a snow strip on Dundee Island, Ellsworth finally reached the Bay of Whales on December 15, 1935. The flight of 2,340 miles occupied 20 hours and 15 minutes, but allowing for landings due to adverse weather, took 13 days to accomplish—including a trek on foot for the last 100 miles to reach the shelter of Byrd's deserted camp.

Renewed interest in Antarctica during the 1930s prompted other nations with eyes on the White South to begin adding aircraft to their expeditions—Norway from its whaling fleets, Australia from the Mawson-led BANZARE (British, Australian, New Zealand Antarctic Research Expedition), and Nazi Germany under Hitler's orders.

Norwegian Aerial Efforts

The Norwegian whaling magnate Lars Christensen introduced aircraft to his whaling fleet in 1929 when the catcher *Norvegia* was modified to carry two float planes—an F.18 Hansa Brandenburg (a type used by the Navy) and a Lockheed Vega high wing monoplane, similar to the type flown by Sir Hubert Wilkins. During December, the experienced aviators Hjalmar Riiser-Larsen and Finn Lützow-Holm began flights along the coast of Enderby Land. On December 22, after stopping at Cape Ann, they raised the Norwegian flag and deposited a notice of the visit in a metal cylinder. Tragedy struck another whaling expedition at this time when, on December 25, pilot Lief Lier and Dr. Ingweld Schreiner disappeared on a flight from the factory ship, *Kosmos* near the Balleney Islands. Their deaths were the first recorded in Antarctic aviation.

A series of flights by Christensen's float planes in January 1930 emphasised Norway's territorial interests. Names were given to the Prince Olav Coast and Sor Rondane Mountains and numerous other features, reflecting the economic importance of claiming prior rights to the wealth of the whaling grounds.

The depot tanker *Thorshavn* sailed south from Cape Town for the 1934 hunting season, carrying an Avro Avian float plane (similar in size to the de Havilland Moth). Between January and February, Lieutenant Gunnerstad completed a series of runs along the Lars Christensen Coast, bestowing names on the King Leopold and Queen Astrid coasts. The third *Thorshavn* expedition of 1936 continues coastal exploration with the aid of radio communication between ship and plane. In the following year a Stinson float plane with a 750-mile range was transferred to the catcher *Firern,* allowing a closer approach to the continent; an obliquely aimed camera recorded parts of the West Barrier, including Olav Prydz Bay and the Kemp and Enderby coasts. On January 27, Ingrid Christensen, the owner's wife, became the first woman to sight Antarctica from the air when the Stinson pilot, Viggo Wideroe, took her on a course above the ice-free Vestfold Hills. Three women friends travelling with Mrs. Christensen were also given the opportunity to fly. When the program ended in early February, 30 hours and 50 minutes had been spent in photomapping, the results to be deposited with the Norwegian Geographical Society. (On January 14, 1939, King Haakon formally claimed Queen Maud Land for Norway, stretching from Coats Land (Britain) to Australian Antarctic Territory, 20° W to 45° E.)

BANZARE and Its Aftermath

Douglas Mawson, Australia's foremost polar explorer, would wait almost 20 years to reach the Antarctic skies after the failure of his first aircraft at Commonwealth Bay in 1911—and his lost chance to wear the laurel of Antarctica's aviation pioneer.

Mawson returned to Antarctica in 1929, leading BANZARE (British, Australian, New Zealand Antarctic Research Expedition) with a de Havilland Moth float plane crewed by two RAAF pilots, Stuart Campbell and Eric Douglas, carried aboard the vessel *Discovery.* Flights were made in January 1930 along the coast of Enderby Land, one of which resulted in the naming of Mac.Robertson Land, in honour of BANZARE's benefactor, a Melbourne toffee manufacturer. The Casey, David, and Masson ranges were also sighted and named.

On the second BANZARE voyage of 1931, further flights of the de Havilland Moth explored the coast of Wilkes Land. On February 9, with Campbell as his pilot, Mawson named Princess Elizabeth Land, after the young woman who would become England's Queen. Other sightings and namings made before the expedition turned for home include the Amery Ice Shelf and the Scullin and Murray monoliths.

In a UK Order-in-Council of February 7, 1933, formal claim was made over the area now known as the Australian Antarctic Territory beyond latitude 60° S and lying between 45° E and 160° E, representing an area of 2,472,000 square miles, equivalent to some 42% of the continent.

Australia sent another expedition to Antarctica in December 1935, on an urgent mission to find the missing American millionaire, Lincoln Ellsworth, and his pilot, Herbert Hollick-Kenyon. RAAF aircraft and pilots Eric Douglas and Alister Murdoch were aboard the vessel *Discovery II,* which left Australia on Christmas Eve. On January 12, 1936, Douglas and Murdoch in a de Havilland 60 Gipsy Moth float plane searched for open water leads through the Ross Sea pack. Two days later, Ellsworth and Hollick-Kenyon were located at the deserted Little America II base on the Bay of Whales. The rescue mission came to a bizarre conclusion when a frustrated Ellsworth protested, "But we're not lost!"

John Rymill was a lesser-known Australian explorer who used aviation to maximum advantage on his small expedition. Born in South Australia, Rymill gained his polar experience in the Arctic and in 1934 formed the 16-man British Graham Land Expedition to map a remote section of the Antarctic Peninsula. Equipment aboard Rymill's motor-assisted schooner, *Penola,* included a motor boat, a tractor, and a de Havilland Fox Moth modified for photo surveying, flown by Wilfred Hampton. Operations were conducted from a first base on the Argentine Islands, then relocated southward to a second base at Marguerite Bay. Rymill insisted on photomapping accuracy through the presence of ground control parties; 1,000 miles (1600 km) of Graham Land's west coast were recorded on camera. The slender but efficient expedition closed in March.

Antarctic Aviation in International Politics

Nazi Germany was not to be excluded from the rush to explore and claim Antarctic territory in the 1930s. Under Adolf Hitler's orders, the Neu Schwabenland Expedition anchored off the Princess Martha Coast of Norwegian-claimed Antarctic territory. Dr. Alfred Ritscher led the ship-based expedition, carrying the Dornier Super Wal flying boats *Passat* (D-ALOX) and *Boreas* (D-AGAT), which were launched by catapult from the seaplane tender, *Schwabenland.* The pilots, Rudolf Wahr and Dicki Shirmacher, and supporting crew had been drawn from Luft Hansa's trans-Atlantic air mail service. A photo-surveying program began between 14° W and 20° E, utilising colour stereo photography, though devoid of adequate ground fixes. Between January 19 and February 5, the Dorniers were aloft for 86 hours, with 63 hours spent on photo missions which covered 140,000 square miles. The numerous German names added to the map were testimony to Hitler's ambitions in the South, which included territorial support claims made through the dropping of swastika-tipped javelins during the Dornier flights. The onslaught of World War II brought Nazi plans for Antarctica to an end.

The end of World War II saw aviation resume over Antarctica, drawing upon vast resources of personal skills and modern equipment that were no longer required for battle. In August 1946, presidential approval was given for the launching of the US Navy Antarctic Developments Project 1947. Known as Operation Highjump, with 4700 members of the Army, Navy, Marine Corps, and Air Force embarked in 123 ships and with twenty-three aircraft, it was the world's largest Antarctic expedition. More correctly described, in a time of cold war tensions, it was a massive polar military exercise.

Rear Admiral Richard E. Byrd (ret.) was officer-in-charge while tactical command belonged to the younger Rear Admiral Richard Cruzen. In October the expedition fleet departed port, bound for a new central base of Little America IV on the historic Bay of Whales. Two additional ship-based groups equipped with Martin Mariner PBM flying boats were sent east and west for exploration of coastal regions below the Pacific and Indian oceans.

On January 29, 1947, six R4D transports (a naval equivalent of the Dakota or DC3) equipped with combined wheel-ski landing gear took off beyond the pack ice from the carrier *USS Philippine Sea.* Led by Commander William ("Trigger") Hawkes, the flight safely reached Little America IV where an advance party of the Seabee construction corps had built a landing strip.

During February a weather-delayed major air operation sent the R4D aircraft on twenty-nine photo-mapping missions covering 22,800 miles (36,480 km) in 220 hours aloft. Flights were made to the South Pole and Victoria Land, beyond McMurdo Sound; by the end of the month the programmed thirty-three flights were completed. A Western Group PBM, piloted by Lt David Bunger, reported sighting an estimated 100 square miles of mostly ice-free rocky coast in region of Vestfold Hills. A landing was made on an open water lake and the water sampled. Late in February final PBM flights of Western Group reached Princess Ragnhild coast of Queen Maud Land; by this time Highjump forces reported having sighted 12.5 million square miles and photomapped one-third of the continent with 65,000 trimetrogon camera exposures; 5,400 miles of largely unknown coast had been sighted.

In contrast to the lavish Highjump, America's most austerely financed and equipped South Polar endeavour was also organised and led by a naval officer. Commander Finn Ronne was the son of Martin Ronne, a sailmaker who served with Amundsen and Byrd; Finn Ronne had been on Byrd's 1933 expedition and in 1940 was second in command of the US Antarctic Service force at Marguerite Bay. Stowed on a former harbour tender that Ronne had "borrowed" from the Navy were three aircraft, also "loans" by courtesy of the Air Force—a Norseman, a Stinson L5, and a twin-engined Beechcraft.

After landing in March 1947 at the derelict US station on Stonington Island, the aviation program commenced on September 22, with an unscheduled rescue flight by chief pilot Captain James Lassiter, USAF, to rescue three Britons who had been forced down when their aircraft failed. Major flights as the summer season advanced were made across the Filchner Ice Shelf and to Gould Bay and the Ellsworth Highland; all were supported by surface sun sights, requiring eighty-six field landings. When the expedition returned in 1948, Ronne's air program had recorded 346 hours aloft and from the Beechcraft's trimetrogon cameras an area of 250,000 square miles were mapped.

The International Geophysical Year

Declaration of 1957–1958 as an International Geophysical Year (IGY) of intense scientific study, much of it focused on the polar regions, signalled the start of an immense logistics support effort in which aircraft were again a prime means of transport and exploration. The US Navy's aviation program commenced in December 1955 with the dispatch of six aircraft to pioneer the 2,400-mile (3840 km) air link between Christchurch, New Zealand, and McMurdo Sound, Antarctica. Led by Rear Admiral George Dufek, commander of Task Force 43—for publicity, known as Operation Deep Freeze—the two R5D Skymasters, and two P2V Neptunes landed on a Seabee-prepared runway at McMurdo after flying time averaging 14 hours. (Two R4D Skytrains were turned back by adverse weather.)

The new year's aviation activity saw a P2V Neptune make a 3,400-mile (5440 km) flight across the South Pole to the Weddell Sea; another flight to Wilkes Land scanned the Davis Sea for a sighting of the first Soviet expedition.

On October 13, an R4D named *Que Sera Sera* achieved the first aircraft landing at the geographic South Pole. Rear Admiral Dufek commanded the flight with pilots "Trigger" Hawkes and Conrad Shinn at the controls. Their journey of 780 miles climaxed on the hard-ribbed snow of the Pole at an elevation of 9,200 ft in –50°C (–58°F) temperature and 15-knot wind. The thrust of all fifteen JATO (jet-assisted takeoff) bottles was needed to lift their aircraft back into the chill air at the bottom of the world for the return flight to McMurdo. The *Que Sera Sera* exploit paved the way for the building of America's IGY Pole observatory, known as Amundsen-Scott Station, which would open on July 1, 1957. To deliver construction material, C-124 Globemasters of the USAF contributed a thrice-daily routine of supply drops which totalled 750 tons by the close of the summer season.

For IGY missions, personnel and cargo lifts to distant bases, and photomapping exercises, fixed wing aircraft of the Navy's special Antarctic VX-6 Detachment included four P2V Neptunes, two R5D Skymasters, nine UC-1 single engine Otters and a number of R4D Skytrains; all except the Skymasters were configured for ski operations. USAF provided summer support of eight C-124 Globemasters (until 1963). In meeting the 1957–1958 IGY requirements, VX-6 crews recorded 1646 separate flights, totalling 5450 hours with an airlift of 5277 passengers and 4050 tons of freight, including oil fuel for interior stations; photo surveys covered 106,000 square miles. Globemasters completed thirty-seven crossings of the Southern Ocean on the route between New Zealand and McMurdo Sound.

Though the IGY closed on December 31, 1958, by presidential decree the Navy's Deep Freeze program continued in support of the National Science Foundation.

Long-Distance Aviation

The turn of the 1960s introduced a decade of larger and more powerful aircraft flying some of the most gruelling exploration missions yet attempted. The first flight from Antarctica to Australia was made on October 24, 1960, by the R7V *El Paisano,* fitted as an airborne laboratory for the Project Magnet hydrographic surveys. The Super Constellation type Navy aircraft completed the 3,700 mile (5920 km) track from McMurdo, across the Pole, to Hobart in 14 hours. The addition of R7V Super Constellations boosted passenger comfort and capacity and travelling time between New Zealand and Antarctica—which, in favourable wind, *Phoenix Firebird* reduced to a record 8 hours and 18 minutes.

Introduction of the C-130BL Hercules transports, mounted on stout wheel-ski gear, began a new era of polar access. On February 22–23, 1963, a C-130BL Hercules (later reclassified LC-130) piloted by Commander William Everett flew a major triangular course from McMurdo to the geographic South Pole and the "most interior point" Pole of Inaccessibility, making a total of 3,600 miles (5760 km) in 10 hours and 40 minutes. Rear Admiral Jim Reedy, commander of the Deep Freeze Task Force 43, was aboard the flight and planned a series of follow-up intercontinental and trans-Antarctic missions, utilising the extended range given by a 3600 gallon auxiliary fuel tank, which fitted within the Hercules' cargo space. With the improved endurance, a Cape Town–McMurdo link was accomplished, via the Pole, across a distance of 4,700 miles (7250 km) in a flying time of 14 hours and 31 minutes.

The LC-130 *Adelie* carried Admiral Reedy and his crew on the final and longest intercontinental journey, which followed a course from Melbourne, across the South Magnetic Pole and geographic South Pole, to Byrd sub-ice station on the Rockefeller Plateau. The flight of September 30, 1964, set the records of first flight from Australia to the Pole and of time and distance spent aloft: from Melbourne, via the Pole, to Byrd Station measured 4,420 miles (7050 km) taking 15 hours and 39 minutes; inclusion of the Byrd–McMurdo leg made the total distance 5,330 miles (8528 km) for 19.5 hours flying time.

Jet age transport came to Antarctica in 1968 with assignment of USAF C-141 Starlifters to the Christchurch-McMurdo route, offering a 40,000 lb payload, and flying time reduced to five hours. (In 1989, the C-5B Galaxy followed, having three times the C-141's payload.)

Commercial aviation history was also made at McMurdo Sound on October 17, 1957, when a Pan American Stratocruiser arrived on a military charter carrying several US and New Zealand dignitaries and two flight attendants. The aircraft spent four hours at the Deep Freeze Base before returning to Christchurch. More than 20 years later, commercial aviation faced a tragic aftermath when, on November 20, 1979, the tourist flight of an Air New Zealand DC10 to McMurdo Sound crashed in whiteout conditions on Mount Erebus, a 12,000 ft volcano, with the loss of all 257 passengers and crew.

That Antarctica had become a vast scientific observatory that permitted the two major aviation participants, the United States and the Soviet Union, to scatter their bases across the continent without fear of trespass or conflict—and air operations were conducted within this same context. The long-range exploration and mapping flights of the Soviet Antarctic Expedition resulted not infrequently in visits to the US Navy's Deep Freeze bases and to those of other participating nations.

The first Soviet expedition of 1956 numbering 100 men, led by Dr. Mikhail Somov, an Arctic expeditionary and Hero of the Soviet Union, established Mirnyy base on the Davis Sea. An aviation program directed by I. I. Cherevichny proceeded within weeks of landing using ski-fitted Li-2 (Dakota style) transports and An-2 single engine cabin biplanes.

By the following summer, an 8,000-ft skiway had been completed at Mirnyy. Li-2 transports began taking off in December on parachute supply drops to the tractor expedition driving an 870-mile (1390 km) traverse to establish Vostok, Antarctica's highest and coldest base at 11,500 ft elevation. A 14-hour flight by an IL-12 across the Pole in October 1958 enabled a Soviet party to make their first visit to the Operation Deep Freeze command at McMurdo Sound.

Major flights completed over the next few years included one of 2,250 miles, carrying expedition leader Dr. Alex Dralkin, from Mirnyy to the subordinate base of New Lazarevskaya on the Princess Astrid Coast of Queen Maud Land. Chief pilot Boris Osipov followed with a major 4,160-mile (6650 km) return flight from Mirnyy to New Lazarev and Wilkes bases. Senior pilot A. Pimenlov took an IL-14 on an 11.5-hour program of photomapping the Pravda Coast and Polar Plateau.

In yet another season of aviation records, chief pilot V. M. Petrov achieved a landing at the Pole of Inaccessibility, 1,367 miles (2185 km) from the coast, on an elevation of 13,450 ft.

Concluding a 15,000-mile (24 000 km) pioneering flight from Moscow, an IL-18D four-engine turbo-prop passenger aircraft accompanied by An-12 transport reached Mirnyy on December 27, 1961, in an airborne time of 44 hours and 46 minutes. Three days later, an Li-2 arrived at Mawson to carry an Australian base member suffering a brain haemorrhage to Mirnyy, 720 miles (1152 km) to the east. Then on January 2, the IL-18D departed Mirnyy on a 1,700-mile (2720 km) mercy mission to McMurdo where the Australian patient was then transferred to a Navy LC-130 for the journey to Christchurch. Within a few years, a schedule of annual intercontinental flights had been established from Moscow, via Mozambique, to the centralised base of Molodezhnaya.

Establishment of More Bases

Two Auster aircraft purchased from the RAF and previously used in the Norwegian-British-Swedish Expedition were taken on the *Kista Dan* voyage of 1955 to make Australia's first permanent base in continental Antarctica.

A three-man RAAF detachment, headed by Flt Lt Doug Leckie, were part of the ANARE (Australian National Antarctic Research Expedition) team that watched their leader, Dr. Phillip Law, raise the Australian flag at Mawson Base on Horseshoe Harbour in Mac.Robertson Land.

With a ski-fitted Auster and a de Havilland Beaver adapted for wheels, skis, or floats, the RAAF crew through the coming summer seasons conducted a wide-ranging series of ferry, supply, and exploration missions. For winter shelter, the hangar built at Mawson was reputedly the then largest structure in Antarctica. Midwinter flights were made to observe the spread of sea ice.

Flights led to the sighting of the Prince Charles Mountains, 160 miles (256 km) south of Mawson, and the Lambert Glacier, 250 miles (400 km) long, varying to 40 miles (64 km) wide, the largest Antarctic glacier, if not the world's largest. Delivery of a second Beaver aircraft allowed expansion of the aviation program including a survey of the Vestfold Hills, 340 miles (545 km) east of Mawson to select a position for ANARE's second base. In September 1957, the first flight arrived at the Soviet expedition's Mirnyy base, 800 miles (1200 km) from Mawson.

Disaster struck the slender RAAF resources on December 28, 1959, when a blizzard with 120-mph wind gusts enveloped Mawson, destroying both Beavers despite tie-down precautions.

ANARE's first twin engine aircraft, an ex-RAAF Dakota, accompanied by its RAAF support crew reached Mawson aboard the supply ship for the 1960–1961 season. Equipped for JATO, trimetrogon cameras and with a four-ton payload, the Dakota promised considerably expanded supply, exploration and mapping programs. However the aircraft's value was short-lived when on December 9, 1960, winds of 116 mph wrecked Mawson's airstrip, tearing both Dakota and Beaver from the tie-down cables and smashing them beyond repair. The remains of the Dakota were found miles away, partly wedged in a crevasse.

In 1963, the RAAF withdrew from Antarctic operations; ANARE flights were transferred to commercial subcontractors, with wider use of helicopters.

The first direct flight from Australia to the South Pole was accomplished on September 30, 1964, by a US Navy LC-130 Hercules transport with two Australian observers among the crew. The 3,600-mile crossing of the Southern Ocean and Australian Antarctic Territory included an overflight of the South Magnetic Pole. After a mail drop at Amundsen-Scott South Pole Station, the historic flight touched down at Byrd Station in the Rockefeller Plateau with a record Antarctic flying time of 15 hours and 39 minutes.

RAAF C-130H transports from No. 36 Squadron joined the supply flights between Christchurch and McMurdo Sound between 1978 and 1982.

On December 29, 2004, 75 years after Douglas Mawson's BANZARE, Australia established an air service to Antarctica, flying in at the beginning and end of the season. The Australian Antarctic Division's two CASA 212-400 aircraft, named *Ginger* and *Gadget,* reached Casey Base after a 2,125-mile (3400 km) flight across the Southern Ocean. A total of twenty-two interstation flights were made before the aircraft returned to Hobart on March 3.

Aviation in the Antarctic Peninsula Region

In postwar years, Argentina and Chile—two South American nations with territorial interests in the Antarctic Peninsula region—renewed an energetic exploration and research program, depending largely on the use of aircraft.

One of the first long distance flights was that of an Avro Lincoln bomber from the Argentine Air Force base at Rio Gallegos in December 1947 which covered the peninsula's northern coasts to observe British military activity. Seaplane flights in 1951 positioned a naval detachment at Esperanza base on Hope Bay. Avro Lincoln flights supplied Army personnel isolated by pack ice at Barry Island and Marguerite Bay. Air operations were expanded to include Beaver, Otter, Neptune, Albatross, DC3 and DC4 aircraft, and naval PBY Catalina and PBM Martin Mariners, with landings on the harbour of Deception Island.

The first Argentinean flights to the South Pole occurred in January 1962. Two DC3 transports commanded by Captain Hermes Quijada presented a plaque to Deep Freeze personnel, honouring the achievements of Amundsen and Scott. Again, in November 1965, an Air Force DC3, configured for JATO propulsion and two Beavers reached the Pole; the DC3 continued to McMurdo Sound, completing Argentina's first trans-Antarctic flight.

By far the longest mission was that of December 6, 1973, when a C-130 transport, commanded by Air Force Chief Brigadier General Hector Fautario, made an 18-hour proving flight of 5,000 miles from Buenos Aires to Canberra, Australia, refuelling en route at Marambio, on Seymour Island.

Chile's already active and successful aviation program incorporated tourism in December 1956, when a national airline DC-6B carried sixty-six passengers from Santiago on a long-range sweep across the Antarctic Peninsula. Grumman HU-1B Albatross flights were later introduced to take passengers and freight to King George Island where visitor accommodation was installed.

While not prominent in long distance aviation, British aircraft made a significant contribution to understanding the Antarctic Peninsula. After World War II, aircraft appeared as an aid to the British whaling industry, commencing off Enderby Land in November 1946. Two Walrus amphibians with a 5.5-hour endurance were stowed aboard the 15,000-ton factory ship *Balaena,* which had been purpose-built with hangar, flight deck, catapult, and crane; the aircraft's original role of assisting navigation through pack ice gradually expanded into whale spotting for the catcher vessels.

Into the 1950s, FIDS (Falkland Island Dependencies Survey, later renamed British Antarctic Survey [BAS]), assumed responsibility for the air exploration program. The FIDS aviation wing comprised Auster, Beaver, and Otter aircraft. In 1955, an aerial contractor, Hunting Aerosurveys Ltd., managed by Chief Surveyor Peter Mott, undertook mapping of the Peninsula and employed two Canso flying boats. Accidents in early years cost BAS the loss of the Beaver and Otter machines.

Crossing the Continent and After

Achievement of the first single engine crossing of Antarctica belonged to a de Havilland Otter cabin aircraft attached to the Commonwealth Trans-Antarctic Expedition (CTAE). As a function of IGY, flights commenced at Shackleton base on the Weddell Sea and then transferred to a subordinate base, known as South Ice, 270 miles (432 km) from the coast. Following the trail of the surface expedition, the course would take them across the South Pole to reach the expedition's goal of Scott Base on Ross Island.

On January 6, 1958, after storm conditions drove a first attempt back to South Ice, the heavily loaded Otter, under the command of chief pilot and RAF aviator Squadron Leader John Lewis, began the 1,430-mile (2290 km) journey. Though facing adverse weather conditions, and climbing to 12,000 ft to surmount the Polar Plateau, 11 hours later the team met an aerial "guard of honour" as they descended to the runway at McMurdo Sound.

Polar aviation profited from the post-IGY enactment of the 1959 Antarctic Treaty in which signatory nations agreed to a "freezing" of their territorial claims and raised no barrier to the continued interchange of weather information and access to the various bases; and to help in the times of need, as testified by an extraordinary record of medical emergency flights, sometimes made in hazardous winter darkness.

The first 50 years of Antarctic aviation were a heroic age of airborne exploration. The great routes were flown. The most remote corners were mapped. Expeditions and their freight were landed to build the bases. Aviation technology progressed amazingly across these decades. Aircraft of the twenty-first century are larger, safer, and packed with electronic aids; satellites underwrite navigation; jet power reduces time and distance. Other more subtle changes have also come to the polar sky. The Navy and its operation Deep Freeze have long departed McMurdo Sound, although there is still a large US aviation presence supported by the US Air National Guard and private helicopter contracts. The Russian Antarctic programme has flown Ilyushin 76TD aircraft from Capetown to Novolazarevskaya in Dronning Maud Land. Many of the air tasks once in the hands of military or government forces have transferred to commercial contractors whose helicopters perform lengthy missions at bases or into the field.

Antarctica no longer belongs to an exclusive club—for the price of a ticket, anyone can gaze from the window of a Boeing 747 on iceberg and glacier. Of course, those who most benefit from air transport in the region today are the scientists and other personnel representing the national programmes conducting work in the Antarctic. Aviation heroes of the first 50 years piloted these paths across the polar sky that, with more comfort, speed, and security, others enjoy today.

David Burke

See also **Antarctic Peninsula; Australasian Antarctic Expedition (1911–1914); British, Australian, New Zealand Antarctic Research Expedition (BANZARE) (1929–1931); British Graham Land Expedition (1934–1937); British National Antarctic *(Discovery)* Expedition (1901–1904); Byrd, Richard E.; Christensen Antarctic Expeditions (1927–1937); Christensen, Lars; Deception Island; Drygalski, Erich von; Dogs and Sledging; Ellsworth, Lincoln; Falkland Islands and Dependencies Aerial Survey Expeditions (FIDASE) (1955–1957); German South Polar *(Schwabenland)* Expedition (1938–1939); German South Polar *(Gauss)* Expedition (1901–1903); International Geophysical Year; Law, Phillip; Mawson, Douglas; Oases; Ponies and Mules; Ronne Antarctic Research Expedition (1947–1948); Ross Ice Shelf; Scott, Robert Falcon; United States (Byrd) Antarctic Expedition (1928–1930); United States (Byrd) Antarctic Expedition (1933–1935); United States Navy Developments Projects (1946–1948); Wilkins, Hubert**

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B

BALLENY ISLANDS

Comprising three large islands (Young, Buckle, and Sturge) and numerous islets and stacks (including Sabrina, Row, Borradaile, Chinstrap, and Monolith), the Balleny Islands are located 66°15′ to 67°10′ S, 162°15′ to 164°45′ E, which is approximately 150 miles (240 km) off the coast of Victoria Land in the Ross Sea region of Antarctica. The archipelago forms a chain that is about 100 miles (160 km) in length, and straddles the Antarctic Circle. Its highest point is Brown Peak (roughly 6000 feet, 1800 m). Sturge Island is the largest, approximately 20 miles long by 8 miles wide (32 by 13 km). The islands are heavily glaciated, with cliffs of rock or ice and a few gravel beaches, and are volcanic in origin, although no recent seismic activity has been recorded.

The Balleny Islands are the only truly marine or oceanic islands (as opposed to continental islands) other than Scott Island on the side of Antarctica that they are on, making them distinctive from any neighboring areas. Their biological diversity exceeds that of any other site in the Ross Sea region.

In 1966, Sabrina Island, located south-southeast of Buckle Island, was designated a Specially Protected Area (SPA), mostly on account of its large colony of Adélie penguins. An attempt was made in 1999 by New Zealand to extend the SPA to cover the entire archipelago within a sea boundary of 12 nautical miles (22 km). Because of their remote geographical location and the difficulty of making a landing on many of the islands, they have been protected from human activities, but, as a consequence, they are also poorly documented. While a preliminary soil fauna analysis has detected mites, nematodes, and bacteria, a comprehensive study of the islands' vegetation is yet to be conducted.

The islands have at least seven species of breeding bird, four species of seal, and twenty-five species of echinoderm. Confirmed bird breeders include Adélie and chinstrap penguins, Cape petrels, snow petrels, Antarctic petrels, southern fulmars, and Wilson's storm petrels. In addition, southern giant petrels, prions, sooty shearwaters, Arctic terns, and skuas have been identified here. The colonies of southern fulmars are estimated to number between 10,000 and 20,000 pairs on the northwest coast of Sturge Island, while up to 10,000 pairs of snow petrels have been estimated on the western cliffs. Approximately 6000 southern fulmars have been counted on Row Island.

The largest colony of Adélie penguins is on Sabrina Island, where approximately 3500 pairs were counted in 1984. Chinstraps are found in smaller numbers, the most notable being the three groups on Buckle Island: Cape Cornish (c. 530 pairs), Cape Davis (c. 500 pairs), and Southeast Promontory (c. 320 pairs).

Seals do not breed on the islands, although several species haul out on the islands' beaches. Weddell seals have been recorded on Row and Borradaile islands, while Weddell, crabeater, and southern elephant seals have been observed on Borradaile Island. Leopard seals have been observed cruising in the offshore waters, probably hunting penguins.

Discovery of the islands occurred on 9 February 1839, when John Balleny of the schooner Eliza Scott and Thomas Freeman of the cutter Sabrina saw them after sailing south from New Zealand in search of new sealing lands on behalf of the Enderby Brothers.

LIZ CRUWYS

See also **Adélie Penguin; Antarctic Petrel; Antarctic Prion; Arctic Tern; Cape Petrel; Chinstrap Penguin; Crabeater Seal; Enderby, Messrs.; Leopard Seal; Shearwaters, Short-Tailed and Sooty; Skuas: Overview; Snow Petrel; Southern Elephant Seal; Southern Fulmar; Southern Giant Petrel; Weddell Seal; Wilson's Storm Petrel**

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BASE TECHNOLOGY: ARCHITECTURE AND DESIGN

The Heroic Era

The early expeditions to Antarctica at the end of the nineteenth and the beginning of the twentieth century were organised to enable new areas and a new continent to be explored. Scientific objectives were set for some of the expeditions, and marine- and land-based surveys were completed. To enable the expeditions and surveys to be supported effectively, buildings and prefabricated structures were erected near the coast, where access was easiest and supplies could be delivered.

The British Antarctic *(Southern Cross)* Expedition of 1898–1900, led by Carsten Borchgrevink, constructed two huts at Cape Adare. They were built from interlocking wooden boards, tightened with steel rods. The roofs were weighed down with bags of coal and boulders to keep the structures in place through the worst of the winter storms. The hut used for living had a double floor and walls, which were insulated with paper. Sliding panels and curtains on the bunks gave some privacy to the occupants of the 19.5- x 16.5-foot (6- x 5-m) structure. A saloon lamp from the supply ship and a double-glazed window with an exterior shutter provided lighting. Medical supplies, bottled provisions, and spare clothing were stored in the loft space. On either side of the porch were two small rooms lined with wool and fur, which were used as a photographic darkroom and for instrument storage and taxidermy. The smaller stores hut was a less developed building and comprised a single-layer uninsulated structure.

The British National Antarctic Expedition (1901–1904), under Robert Falcon Scott, erected the Discovery Hut, measuring 24.5 by 22 feet (7.5 x 6.75 m) at Hut Point in McMurdo Sound in 1902. This structure, as with many of the early buildings, remains today where it was originally erected, in a preserved condition. Discovery Hut served as a storeroom, laboratory, and theatre for the expedition members who lived on the ship *Discovery,* moored alongside in Winter Quarters Bay. Purchased in Australia at a cost of just over £360, the hut was supplied in prefabricated form with an awning on three sides. This type of building was very common in Australia at the time and has double-thickness walls and floor, insulated with felt. The hut was subsequently used by three other expeditions of the Heroic Era.

Many other buildings erected at the turn of the nineteenth century were of a similar prefabricated form to Discovery Hut. Admundsen's Framheim base of 1911, however, included a building that he described as an ordinary Norwegian house. Copying the Scandinavian building techniques of the time, the insulation was significantly enhanced. Using sandwich-type layered walls, a central 3-inch-thick layer of cellulose pulp was surrounded on each side by 3-inch-thick wood, fabricated from interlocking wooden planks. Between the wooden planks and the inner and outer 1-inch-thick wooden layers was a 1-inch air gap. A weatherproof layer was affixed to the inside of the outer wooden layer.

That many of these early structures still remain is testament to the skills of the many individuals who repair and maintain the buildings. The dry atmosphere in Antarctica also helps to ensure that the wooden structures are preserved.

After the Heroic Age, surveys and expeditions continued with some buildings and bases erected to support activities. The increase in science at the bases led to laboratory space's becoming a more important feature, as equipment and technology started to develop. The buildings were still rather primitive and were usually pitched-roof wooden huts with limited insulation.

World War II prompted a limited building campaign. In 1943, the British government sent members of Operation Tabarin to the Antarctic Peninsula to establish small bases to deny shelter for enemy ships and submarines and to assert territorial claim. Prefabricated wooden buildings manufactured by a company called Boulton and Paul were supplied for Tabarin. Erected on rock foundations, these buildings had facilities for biology, geology, and meteorology but were essentially wooden shells with limited insulation.

Facilities to Support Science

It was not until the 1957–1958 International Geophysical Year (IGY) that building work in Antarctica started in earnest. The major investment in science that was prompted by IGY had to be matched by new buildings and bases to support the science. Bases used to support field surveys and expeditions started to become stations with infrastructure and accommodations to enable complex science programmes to be developed.

The majority of the buildings in Antarctica are still built near the coast on rock foundations. Portal frame buildings with either wood or steel frames are erected on concrete piers or plinths. Most structures use prefabricated sandwich panel walls and floors with integral insulation, vapour barriers, and an outer protective skin. Wood is a very effective building material. Coated fibreglass and other materials have been used, but often suffer from UV degradation and can fracture in very low temperatures. Steel is used as a structural component but care must be taken to avoid cold bridging where the low external ambient temperature is conducted through to the inside of the building. As older buildings are replaced, insulation is improved, environmental impact is reduced, and the demand for more highly serviced facilities increases to meet the needs of science.

Building on the Ice Shelf and Polar Plateau

New stations were erected for IGY far inland, at Amundsen-Scott South Pole Station (US) and Vostok Station (Russia). Building inland and on ice presents many challenges that are not apparent near to the coast and on rock foundations. All materials, equipment, fuel, and consumables must be shipped to the base. The climate is normally less hospitable than at the coast and the period available during the Antarctic summer to erect new buildings is more limited. Compromises have to be made between the size of prefabricated sections that can be transported to the site by aircraft or tractor train and the number of personnel needed to build the structure. Both the South Pole (9500 feet or 2900 m) and Vostok (11,443 feet or 3488 m) are at high altitude, and simple tasks become difficult. The extreme cold necessitates the wearing of thick and often bulky clothing, which restricts movement and slows assembly work; the lowest-ever-measured temperature on earth of –89.3°C was recorded at Vostok. Any materials or tools left on the surface are warmed through solar radiation and sink into the ice; spare tools and materials must be taken to the site. The difficulties associated with building inland and in extreme conditions require innovative design, and the logistics associated with moving materials to site are challenging.

In addition to these construction and transportation issues, snow accumulation, drift, and melt create another set of challenges. Snow is blown from the centre of Antarctica to the edge of the continent, causing drifts and an increase in the mean snow level. This effect is particularly pronounced away from the centre of Antarctica. Any structure on the surface impedes blown snow, reducing the velocity of the snow, leading to snow drifting. Moving snowdrifts is an expensive and time-consuming operation.

Even at the South Pole the level of the snow increases by several centimetres per year, causing any structures to sink below the surface over time unless remedial action is taken. A dome structure was erected at the South Pole in the early 1970s. The dome is now well below the surface and being crushed by the surrounding ice. A new building is being erected on legs that can be jacked to keep the building above the surface. Extensive snow modelling was undertaken at the design stage to ensure that the building was oriented at the most suitable angle to reduce snow drifting. Snow modelling is achieved through numerical models, which are run on computers. Physical models are also built and particles suspended in water flow around model buildings, developing drifts. Considerable experience of the polar environment is needed to interpret the models to ensure they are representative of the real environment.

Halley Station was first built by the UK for the IGY on the Brunt Ice Shelf. Halley is located at the southern end of the Weddell Sea off the Caird Coast of Coats Land. The surface of the floating ice shelf, which is up to 1300 feet (400 m) thick, increases in height by between 3 and 5 feet (1 and 1.5 m) each year due to blown snow. This increase in the average height of the ice shelf is offset by melting from underneath the shelf. As a floating ice shelf, it is connected to the continent and flows towards the sea at between 1300 and 2600 feet (400 and 800 m) per year. Any building constructed on the surface and inland from the ice edge gradually sinks below the surface and also reaches the edge of the ice shelf. The current Halley Station, Halley V, is built on jackable legs, which are raised each year to overcome the effects of the buildup of snow. All previous stations were built on the surface and allowed to sink. Access was by vertical shafts and slopes for vehicles. The stations were occupied until they became unacceptably deep for personnel or distorted due to pressures in the ice. Other techniques to overcome the buildup of snow have included large ski-mounted buildings, which are moved each year onto raised ice platforms.

Design for Liveability

The majority of the structures erected in Antarctica have been designed by engineers for ease of construction, maintainability, and reliability. Architectural considerations have often been secondary, with personal space for staff limited and the delights of home added by the personnel who winter on the station. The challenges of construction in a hostile environment and the high cost of construction limit the budget available for enhanced features. The designs of the next generation of stations, started by the US Programme at the South Pole, followed by the UK at Halley VI and the German Alfred Wegener Institute (AWI) at Neumayer 3, have all been led by architectural teams. Although there will always be a need to ensure that any structure in Antarctica is maintainable, architects are being used to provide an environment for staff that will motivate them, living in a hostile working environment.

Environmental Considerations

As well as the introduction of architectural features to enhance living conditions for personnel, producing a sustainable building with low environmental impact is now very important. The Swedish Polar Institute recognised the value in a low-energy facility when building Wasa Station at Vestfjella in Queen Maud Land between 1988 and 1989. The design incorporates a wide range of technologies to reduce energy consumption and solar panels to generate most of the electrical power. The foundations are designed to be easily removed when the station is decommissioned. A very high level of insulation is used to reduce the demand for supplementary heating. Although only 57 by 25 feet (17.5 x 7.6 m), the building houses up to sixteen people and has a kitchen, common room, sauna, shower, and laundry room, demonstrating what can be achieved to reduce the impact of human habitation on Antarctica.

DAVID BLAKE

See also **Amundsen, Roald; Amundsen-Scott Station; Antarctic Peninsula; Base Technology: Building Services; Borchgrevink, Carsten E.; British Antarctic *(Southern Cross)* Expedition (1898–1900); British Antarctic Survey; British National Antarctic *(Discovery)* Expedition (1901–1904); International Geophysical Year; Norwegian *(Fram)* Expedition (1910–1912); Scott, Robert Falcon; Vostok Station**

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BASE TECHNOLOGY: BUILDING SERVICES

The stations and bases erected in Antarctica at the beginning of the twentieth century were often poorly insulated and had very rudimentary services installed. In the second half of the century, as Antarctic bases have increasingly been built to support science activities, building services and facilities have been greatly enhanced to meet the expectations of staff and to enable high-quality science to be delivered. Ensuring that the buildings have minimal impact on the Antarctic and that energy demand is reduced, are also major objectives. All basic services and utilities including electrical power, water, sewage, and communications have to be produced and/or delivered on site in Antarctica.

Power Supply

There are no readily available sources of hydrocarbon fuels in Antarctica. Renewable-energy systems are being installed to provide electrical power and heating; however, mature and reliable technology and equipment that will continue to function under the extremes of the Antarctic environment are difficult to source. Imported hydrocarbon-based fuels continue to be an important source of energy to power the building services that are essential for living and working effectively.

Electrical power is the primary utility. It is used to directly or indirectly provide water, heating, and sewage disposal and treatment and to operate other services and facilities including communications. There are normally three generator sets on each station, although some sites have multiple generators, which are brought on line as power demand increases. The traditional layout of three generator sets is configured with one generator on line, another on standby, and the last undergoing maintenance. Loss of electrical power can have serious consequences and a standby set is essential. As an example of the potential impact of the loss of a generator, electrical power is often used to heat pipes that carry fluids; a loss of power rapidly leads to burst pipes and leaking of fluids into the environment. The frequency and voltage of electrical power supplies are generally the same as are found in the parent country that operates the station.

Hydrocarbon Fuels

Hydrocarbon fuels used in the generator sets are derivatives of either aviation turbine fuel or marine gas oil. Aviation fuel, known as JP1 or AVTUR, has the advantage of a lower freezing point than marine gas oil. It has a lower lubricity than marine gas oil and lubrication oil is often added to reduce engine wear. Marine gas oil (MGO) is similar to the diesel fuel used in cars and trucks, although additives are included with the fuel to stop waxing or solidification in subzero temperatures.

Fuel is supplied to Antarctic stations in bulk, carried by supply ship or tanker, or in 45-gallon drums. To transfer the fuel to inland sites either aircraft tankers or tractor trains are used. The Protocol on Environmental Protection to the Antarctic Treaty places great emphasis on eliminating fuel spills and in consequence all new fuel facilities have double-skinned fuel tanks or bunds to stop fuel from escaping into the environment should a leak develop. The Council of Managers of National Antarctic Programmes (COMNAP) has provided guidelines for storage and transport of fuel. Ensuring the safe and effective delivery and storage of hydrocarbon fuels is a very resource-intensive process. Delivering energy-efficient power-generation systems with reduced hydrocarbon consumption is a key objective for nations operating in Antarctica.

To reduce the use of fuel, the most effective approach is to reduce the need for energy by enhancing building insulation and encouraging efficient use. Energy recovery can also be maximised by extracting waste heat from generator cooling jackets and exhaust stacks for use in heating buildings and for converting snow and ice into water. Balancing power loading through the day by, for example, not washing clothes or showering when cooking ovens and other high-demand facilities are operating also improves fuel use efficiency. The very severe external environmental conditions on Antarctic Stations necessitate that reliability be considered as well as energy efficiency. Renewable-energy systems have applications in Antarctica, but their suitability requires very careful consideration.

Wind, Solar, and Water Power

For wind generators to work most effectively, a consistent wind speed, predominantly from one direction, is required. Wind gusts can cause damage to turbine blades. Ideal wind conditions are not readily available in Antarctica, with high winds often followed by days of calm. In coastal and marine areas, riming or ice buildup on turbine blades can lead to early equipment failure. Gearbox failure due to very low temperatures is another challenge. Despite these challenges, there are successful wind-power installations in Antarctica. The Australian Antarctic Division has three 300-kW wind turbines at their Mawson Station. In operation, these turbines, which are assembled without gearboxes, produce an average power output of 100 kW.

To enhance output efficiency, power-storage systems are needed to store power when wind is generated at optimum speed. Energy-storage technology remains a challenge for temperate climates as well as Antarctica, and backup hydrocarbon-fuelled generators are essential.

Photovoltaic (PV) cells harnessing solar energy are another renewable power source used in Antarctica. The lack of overhead sun means that the angle of elevation and operating efficiency can be low. During the summer months it is possible to also collect light through reflection off the snow surface. During the long winter there is no incident radiation and no electrical power produced. PV panels have many applications for powering instrumentation, communication systems, and other field camp equipment, but their application for building services requires careful evaluation.

On sub-Antarctic islands where there is free-running water in the summer months, water turbines have been used to generate electrical power. Wave generators offer an opportunity for the future when the technology has matured. These systems make use of sea swell, which is at its maximum in the polar regions. Polar operators continue to research and develop new opportunities for installing renewable-energy systems on Antarctic stations whilst reflecting on the need to maintain reliable power.

Water Production

Although 70% of the world's fresh water is in Antarctica, it is locked into the continent as snow and ice. The simplest form of technology used to produce water is a snow melter. Snow and ice are put into a tank and heat applied to produce water. Waste heat from generators is often used and passed through heat coils around or inside the tank.

A mechanical means of moving snow and ice, or personnel using shovels, is a feature of snow melters. One technique used to eliminate the moving of snow is to construct a Rodriques Well. Hot water is produced at a high pressure, then pumped into the snow. As the snow melts, the accumulated water is pumped to the surface. This technique has been successfully employed at the South Pole Station but requires a significant volume of fuel to produce the hot water needed to pump into the snow.

Stations built near to the sea can make use of alternative techniques to produce water. The most common approach is the reverse-osmosis system. These units pass water at a pressure of 70 Bar through a membrane. Pure water passes through the membrane, and brine that does not pass through is returned to the sea. The fresh water produced is very pure and soft; minerals are added to balance it. Desalination can also be achieved using evaporators where seawater is heated and the fresh water condensate is extracted.

Reticulation of water through external pipework requires insulation around the pipework to protect against freezing. Heat tracing of the pipes is also often needed. Either electrical heating tape or small-bore hot water pipes are wrapped along and around the pipes carrying the freshwater. Heat-trace systems add to the overall energy budget of the station.

Waste Treatment

The processing of sewage and bulk waste fluids is essential unless all waste is returned via ship. The large volume of sewage makes removal by ship impractical for most sites. Untreated human sewage is passed through macerators, which cut and chop the solids into small pieces suspended in the waste water. At coastal sites the wastewater may be pumped into the sea for natural biological processes to digest the sewage. At inland sites the waste or grey water can be pumped into the ground. The temperature of the grey water is sufficient to melt the ice and develop a chamber where the waste is stored. Although the numbers of personnel on most Antarctic stations are low and the current procedures are within the requirements of the Protocol on Environmental Protection, most Antarctic operators are now installing sewage-processing systems. Both first-stage and biological processing systems are being installed to ensure that the waste water that is left on the continent is as pure as possible and does not contain any pathogens. Recovered solids are dried and removed from Antarctica. The sewage-treatment plants, like the heat-trace systems, add to the overall energy budget for the station.

Heating

Waste heat produced by generators and other plants can be recovered and used to provide background heating for buildings. If high-U-value insulation material is used in structures, then the heat-recovery system can provide most of the heating needs of the structure during the winter months. Boilers using hydrocarbon fuel are required to back up the recovered heat systems and are also needed where no heat-recovery systems are installed. MGO and AVTUR are the primary sources of fuel for the boilers. The heat is distributed around the buildings using radiators and hot water or via pumped air when the buildings are air-conditioned. Buildings are either double- or triple-glazed to avoid heat loss.

Fire Protection

The environment in the Antarctic is very dry and buildings are normally constructed from wood. The combination of the dry atmosphere, wooden buildings, and heavily serviced facilities ensures that fire detection and protection procedures are always considered when risks are assessed. Fire remains a significant risk in Antarctica. Should a fire develop in the middle of winter, personnel on site may have great difficulty in fighting the fire when there is a very low external temperature or there are high winds. All station personnel have to be trained to deal with a fire should one develop. Only the very large stations have a full-time fire service.

Fire and smoke detectors are installed in all buildings unless they are very remote or it is difficult to connect the building to the fire-detection system. Station personnel are trained to extinguish a fire, but should it take hold, the structure will be left to burn through. Emergency shelters or alternative buildings with food and supplies would be activated if a fire engulfed an accommodation building.

On some stations, fire-suppression systems are installed to stop flames from spreading should a fire develop. Standard water sprinkler equipment and mist systems are installed to protect accommodation buildings and other important structures. Should the sprinklers be activated, they soak a structure in water to stop the fire. In winter the structure may then be uninhabitable. It is therefore important to reduce the risk of any fire developing and ensure that personnel are aware of the hazards and how to reduce risks.

Communication Systems

Communication systems are installed by the Antarctic operators for sending logistical and scientific data to their headquarters. These systems are also used for transmitting data on the performance of the services installed on stations to enable engineers to monitor the sites. Although installed for operational reasons, communications are also important for the morale of station personnel. Being able to contact family and friends and other Antarctic stations is very important to staff.

Satellite communications carrying voice and fax use dial-up carriers with bandwidths of up to 64 kbps and similar to a home computer dial-up connection. Broadband connections with 24/7 availability enable Internet access and e-mail. Despite the availability of satellite communications, around Antarctica, high-frequency (HF) and very-high-frequency (VHF) radio systems are still used for routine communications.

Services on Antarctic stations ensure that personnel have access to facilities that enable them to deliver high-quality science and maintain a comfortable living experience. The challenge for the engineer providing the buildings and facilities is to ensure that they are sustainable and have a minimal environmental impact. These goals often conflict with the need to keep systems reliable and maintainable. As technology develops and stations are replaced, matching reliability with sustainability becomes more achievable.

David Blake

See also **Base Technology: Architecture and Design; Council of Managers of National Antarctic Programs (COMNAP); McMurdo Station; Protocol on Environmental Protection to the Antarctic Treaty**

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BEACON SUPERGROUP

H. T. Ferrar (1907), the geologist on the British National Antarctic *(Discovery)* Expedition, named Beacon Sandstone for nearly horizontal, light-colored sandstone intruded and commonly capped by dark dolerite sills. The name came from extensive exposures of sandstone on Beacon Heights, a group of hills in the upper reaches of the Taylor Glacier, 130 km due west of the Discovery Hut and the present McMurdo Station. The name has since been used informally for just about any late Paleozoic–early Mesozoic sandstone in East Antarctica, but mainly refers to the sedimentary sequence above Proterozoic–lower Paleozoic igneous and metamorphic basement (Kukri Erosion Surface) and below volcanics of the Jurassic Ferrar Group in the Transantarctic Mountains. Harrington (1965) formalized the term Beacon by giving it supergroup status, subdividing it into the Taylor Group of Devonian age separated by a major disconformity from the Upper Carboniferous to Upper Triassic Victoria Group. These groups have been further subdivided into local formational units throughout the Transantarctic Mountains.

The age of the Beacon has been determined by a series of historic discoveries. Plant remains and trace fossils were found in the McMurdo Sound region during Robert Falcon Scott's 1901–1904 *Discovery* Expedition, but were not diagnostic in assigning an age at the time. During the 1907–1909 Nimrod Expedition, Shackleton's party collected fossil wood from a moraine near "The Cloudmaker" on December 11, 1908. Six days later, higher up the Beardmore Glacier, they reported several coal seams in the upper part of a 1500-ft-thick Beacon sandstone sequence on the east side of Buckley Island (Shackleton 1909). The fossil wood was identified as coniferous and dated as no older than Lower Carboniferous or Upper Devonian. Beacon ages were finally established by collections from Scott's 1911–1913 *Terra Nova* Expedition (Scott 1913). On February 8, 1912, on return from the South Pole, Scott's party collected plant-bearing samples from the east face of Buckley Island on the upper Beardmore Glacier. During the following summer the rescue party recovered these samples from Scott's last camp. From this collection Seward (1914) identified leaves of Glossopteris, a late Carboniferous–Permian plant. Also, during the *Terra Nova* Expedition, Debenham found well-preserved Upper Devonian fossil fish plates in Beacon erratics in a moraine on the Mackay Glacier near Granite Harbour in the McMurdo Sound region (Woodward 1921). Gunn and Warren (1962) eventually found outcrops containing fragmentary fossil fish remains in the Boomerang Range, Lashly Mountains, and Mount Feather along the margin of the polar plateau in the McMurdo Sound region. Gunn and Warren (1962) also extended the upper age limits of the Beacon by finding a Triassic Dicroidium flora at several localities along the margin of the polar plateau. Long (1964) extended Beacon ages downward with the discovery of a Lower Devonian marine invertebrate fauna in the Ohio Range.

The Glossopteris flora in Antarctica was proof of Gondwana connections, but Seward (1914) was more concerned with the climatic implications than how the flora got there. He did mention a possible land bridge between South America and the Antarctic Peninsula. Woodward (1921) compared Upper Devonian freshwater fish fossils in Antarctica with those of Europe and North America, but did not speculate on how they were dispersed across the globe. In spite of convincing evidence of a Gondwana supercontinent put forward by Alfred Wegener (1929) and Alexander du Toit (1937), most geologists in North America and Europe did not accept continental drift theory until the late 1960s, when accumulated geophysical evidence of plate tectonics became overwhelming. Geologists of the International Geophysical Year (1957–1958) and later had already recognized the similarities in the geology of Antarctica and other Gondwana continents. Long (1964), working in the Horlick Mountains, was the first to identify the uppermost Carboniferous–Lower Permian glacial beds. These have since been found throughout the Transantarctic Mountains and in the Ellsworth Mountains. Undeniable proof of a direct connection between southern Africa and Antarctica came with a series of reptile and amphibian fossil finds in the Beardmore and Shackleton glacier areas (Barrett et al. 1968; Elliot et al. 1970; Hammer 1995). The Lystrosaurus and Cynognathus zone faunas from Antarctica have several species in common with South African faunas from the Karoo Basin.

The Beacon was deposited in sedimentary basins roughly along the trend of the present Transantarctic Mountains (Collinson et al. 1994). These basins appear to have been extensional until the mid-Permian when an oceanic trench and volcanic arc developed along the Panthalassan Ocean margin of West Antarctica. In the Late Permian and Triassic the Transantarctic basins evolved into an elongate basin bordered by a mountainous fold belt in West Antarctica. Beacon deposition ended by the Early Jurassic with rifting related to the dispersal of the Gondwana continents.

The Permian–Triassic Transantarctic basin may have been contiguous with similar basins along the Panthalassan Ocean margin in Australia (Sydney-Bowen basin) and in South Africa (Karoo basin) (Collinson et al. 1994). The stratigraphic sequence in Victoria Land is similar to that of Australia, whereas the sequence in the rest of the Transantarctic Mountains is similar to that of South Africa. The Beacon sequence is also typical for Gondwana because these continents shared similar climatic histories in a southern polar region. The Victoria Group begins with Upper Carboniferous to Lower Permian marine or terrestrial glacial deposits. Post-glacial black shale, representing a vast inland sea, extends from the Nimrod Glacier to the Horlick Mountains. This seaway may have extended to the Ellsworth Mountains in West Antarctica, the Karoo Basin in South Africa, and the Paraná Basin in southern Brazil. The middle to Upper Permian throughout Antarctica is represented in coal-bearing river deposits. Coal deposition stopped abruptly at the end of the Permian. Early Triassic global warming permitted reptile and amphibian faunas from South Africa to migrate into polar Antarctica, where they were buried in river channels and on floodplains. Coal deposition resumed again in the Middle and Late Triassic.

Although parts of the Beacon might be good reservoir rocks for oil and gas deposits, marine organic source rocks are sparse. In addition, the heat and hot fluids generated by the intrusion of Ferrar dolerite throughout the Beacon sequence in the Transantarctic

Mountains have driven out most of the volatiles in the organics and coal, rendering them unsuitable for exploitation (Rose and McElroy 1987).

James W. Collinson

See also **British Antarctic *(Nimrod)* Expedition (1907–1909); British Antarctic *(Terra Nova)* expedition (1910–1913); British National Antarctic *(Discovery)* Expedition (1901–1904); Coal, Oil, and Gas; Debenham, Frank; Ferrar Supergroup; Fossils, Invertebrate; Fossils, Plant; Fossils, Vertebrate; Geological Evolution and Structure of Antarctica; Glacial Geology; Gondwana; International Geophysical Year; McMurdo Station; Plate Tectonics; Scott, Robert Falcon; Shackleton, Ernest; Transantarctic Mountains, Geology of; Wild, Frank; Wilson, Edward**

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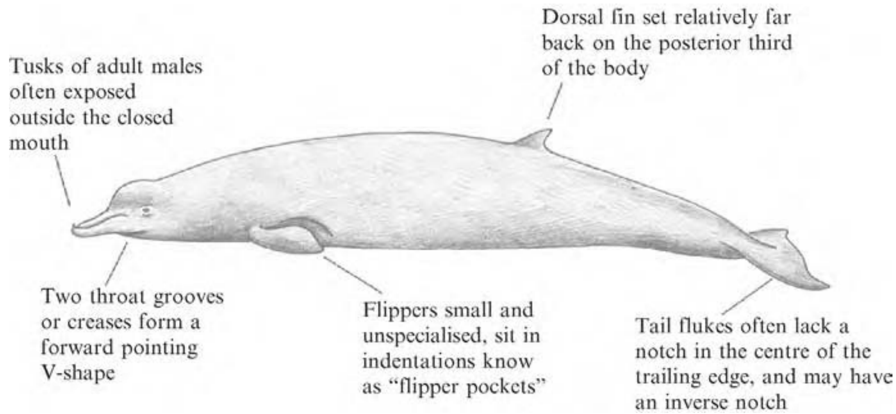
BEAKED WHALES

The beaked whales or ziphiids—so called due to their family name of Ziphiidae—are the most enigmatic of the families of toothed whales (the odontocetes). In fact, they are so difficult to observe at sea that several species have never been seen alive! They are medium-sized cetaceans (the group comprising whales, dolphins, and porpoises), with adults ranging from 3–13 m in length. They tend to live far offshore in areas of deep water (usually over 300 m deep), where they perform long, deep dives in search of their squid and fish prey. In addition, many beaked whale species are similar in external appearance, so their identification at sea is often difficult for an inexperienced observer. Together, these have made the study of beaked whales much more difficult than that of more accessible, near-shore cetacean species, and as a result we know relatively little about this group of animals.

This situation has improved in recent years; with rapidly developing techniques in molecular analysis, and field efforts to obtain skin samples from different species, there has been a surge in knowledge about beaked whale systematics and biology. Currently there are thought to be twenty species from six genera in this group. However, the taxonomy of this group is still relatively uncertain and new species are regularly described and old species revised.

The common name of the family, beaked whales, refers to their long and slender rostrum, which results in a prominent beak in most species. This beak blends into their high forehead (or melon) without the break or groove that is characteristic of most other delphinids. An evolutionary trend in most ziphiids has led to



A typical beaked whale showing characteristic features.

a reduction in their number of teeth. Females and immature males are essentially toothless (the teeth do not erupt), and adult males have retained only a single pair of teeth in the lower jaw. Two exceptions are the genus *Berardius,* which has two pairs of mandibular teeth in the lower jaw of both adult males and females, and *Tasmacetus,* which has a full set of teeth in both upper and lower jaws of both sexes. These teeth in adult males are often exposed outside the closed mouth and so can be considered tusks. Males of different species have these teeth in different positions in the lower jaw, and the teeth often vary in size and shape, becoming much enlarged in some species. These are often the most reliable way to tell different beaked-whale species apart, but in rough sea conditions it is usually difficult to see the teeth well enough for this, even if an adult male is present!

Other features that distinguish beaked whales from other groups include the possession of two conspicuous throat grooves or creases that form a forward-pointing V shape, and the lack of a notch in the tail flukes. Their flippers are relatively small and unspecialised and often sit in "flipper pockets," indentations in the body thought to increase streamlining. The dorsal fin, which is set relatively far back on the posterior third of the body, is small and triangular rather than falcate. Their skull morphology is also unique, exhibiting elevated maxillary ridges behind the nasals. Most beaked whales have asymmetrical skulls, although *Berardius* and *Tasmacetus* have nearly symmetrical cranial characteristics.

Population Status, Distribution, and Habitat Use

Of twenty species of beaked whales currently known (new species were recognised in 1995 and 2002), eleven may be encountered in the Antarctic or at the waters of the Polar Front. The majority of beaked-whale species are found offshore in deep waters. The two species found farthest south are the southern bottlenose whales and Arnoux's beaked whale, which may be observed near the ice edge in summer. These two species have the largest body size of the beaked whales found in the Antarctic. Gray's beaked whale and the strap-toothed whale are found south of the Polar Front from 30°–60° S. There are also occasional sightings of Cuvier's beaked whales this far south. Andrew's beaked whale, Hector's beaked whale, and Shepherd's beaked whale tend to be found slightly farther north, generally north of the Polar Front. The ginkgo-toothed beaked whale has been observed south of New Zealand and the Chatham Islands; True's beaked whale is known only from strandings in South Africa and southern Australia, while the recently identified spade-toothed whale is known only from two specimens in New Zealand and one in the Juan Fernandez Islands.

The most common beaked whale in the Antarctic is the southern bottlenose whale, of which there are thought to be about five hundred thousand in summer. However, difficulty in detecting and identifying other beaked whales has meant that there are no estimates of abundance for other species. The status of all beaked whales is currently listed by the IUCN (International Union for the Conservation of Nature) Red Book as "insufficiently known."

Life History

Based on data on ectoparasites and stomach contents, it has been suggested that southern bottlenose whales may undertake seasonal migrations between subtropical and colder waters, with sightings off Durban

Antarctic Beaked Whales

Species	Latin Name	Adult Size (m)	Distribution	Group Size	Lifespan
Arnoux's beaked whale	*Berardius arnuxii*	M <9.8 F 9.8	Southern ocean to ice edge; northerly limit 34° S	Usually around 10; up to 80	Unavailable (B. bairdii male 84 years, female 54 years)
Southern bottlenose whale	*Hyperoodon planifrons*	M 6.9 F 7.5	Southern ocean to ice edge	Less than 10	Unavailable (H. ampullatus at least 37 years)
Cuvier's beaked whale	*Ziphius cavirostris*	7	Global	-	Probably 40 years, possibly more than 60
Shepherd's beaked whale	*Tasmacetus shepherdi*	6–7	Southern temperate	-	Unavailable
Strap-toothed beaked whale	*Mesoplodon layardii*	M 5.9 F 6.2	Circumglobal in temperate and sub-Antarctic southern waters	Up to 3	Unavailable
Gray's beaked whale	*Mesoplodon grayi*	M 5.7 F 5.3	Circumglobal in temperate waters of Southern Hemisphere (30°–45° S)	1–2 (stranding of 28)	Unavailable
Hector's beaked whale	*Mesoplodon hectori*	4.2	Circumglobal in temperate waters of Southern Hemisphere	-	Unavailable
Ginkgo-toothed beaked whale	*Mesoplodon ginkgodens*	M 4.8 F 4.9	Temperate and tropical Indo-Pacific, records off New Zealand and Chatham Islands	-	Unavailable
True's beaked whale	*Mesoplodon mirus*	5.3	Temperate North Atlantic and temperate Southern Indian Ocean	-	Unavailable
Spade-toothed beaked whale	*Mesoplodon traversii* (previously *M. bahamondi*)	?	Southern temperate	-	Unavailable
Andrew's beaked whale	*Mesoplodon bowdoini*	M 4.5 F 4.9	South circumpolar, north of Polar Front	-	Unavailable

(30° S) showing peaks in February and October, potentially representing northward and southward migration. Sightings surveys have also shown a reduction in beaked-whale density in Antarctic waters after mid-January. However, sparse data are not ideal for identifying movements of animals, and so these results should be viewed with caution until more rigorous methods of identifying migration with some degree of certainty have been obtained.

As with other cetaceans, the best method of age determination is the examination of growth layer groups (GLGs) in the teeth. These are similar to tree rings, so counting the layers in the teeth allows researchers to calculate an animal's age. In general, many beaked whales appear to reach sexual maturity at 7–10 years and live to approximately 30 years of age. However, teeth from few Antarctic beaked whale species have been analysed.

Social Structure

The social organisation of the majority of beaked-whale species is poorly known. Their shyness at sea means that for many beaked-whale species, the data that we have on group sizes are nonexistent or based only on occasional sightings or strandings. These limited observations have suggested that many species may be found in small groups of one to six animals. However, mass strandings are occasionally reported, including a stranding of twenty-eight Gray's beaked whales in New Zealand. Arnoux's beaked whales are the most gregarious of the Antarctic beaked whales, often gathering in groups of six to ten and occasionally up to fifty or more, and showing behavioural synchrony during diving and surfacing.

The composition of their social groups is similarly unknown, particularly for Antarctic species. Based on the linear scars that crisscross the bodies of many adult males, it seems that the tusks of males are used as weapons in aggressive encounters with each other, presumably for access to females. The two beaked-whale species that have been studied in most detail are the northern bottlenose whale and Baird's beaked whale, in the North Atlantic and North Pacific, respectively. Northern bottlenose whales possess only small teeth, but instead male–male conflict appears to consist of head-butting using the large flattened melon (and underlying enlarged maxillary crests). However, long-term photo-identification studies have suggested stronger associations between males than between females in this species. Anatomical studies of groups of Baird's beaked whales taken in the continuing fishery off Japan suggest an unexpected social structure in this species. Both males and females of this species possess erupted teeth, and females are slightly larger than males. Males appear to reach sexual maturity at an average of 4 years earlier than females and may live for up to 30 years longer. This has led to speculation that males may be providing parental care in this species, although further work is needed to confirm this.

Diet and Trophic Interactions

The majority of beaked whales are thought to feed primarily on epibenthic and mesopelagic squid, although some mesopelagic fish may also be taken. The reduced dentition of these species is thought to be due to this dietary specialisation. Shepherd's beaked whale, the exception to this, has a diet that appears to consist primarily of bottom-dwelling fish. The reduced dentition of the beaked whales, together with their narrow jaws and throat grooves, has been suggested to function in suction feeding. Among the males of species such as the strap-toothed whale, the elaborate growth of the strap-like teeth may limit the aperture of the gape to a few centimetres, and it is difficult to see how prey-capture techniques other than suction feeding could be successful.

Beaked-whale species are known to be excellent divers. Dives of up to 1 hour have been recorded from several beaked-whale species, although many of these records have been based on surface observations of diving whales and so there is a possibility that some of the breathing events might have been missed accidentally. Small microcomputers that record depth at preset time intervals are becoming widely used to look in detail at the diving behaviour of marine mammals, although the attachment of these to cetaceans is not easy (particularly for beaked whales, which are notoriously difficult to approach). Results from a handful of animals (thus far northern bottlenose whales and Cuvier's beaked whales) corroborate previous suggestions as to the deep and long dives of these whales.

Acoustics

Different beaked-whale species appear to exhibit quite different acoustic repertoires. Some species (such as Baird's beaked whale) produce the social whistles characteristic of other toothed whales, although others (such as the northern bottlenose whale or Cuvier's beaked whale) produce primarily or solely echolocation-type clicks. Recordings made from Baird's beaked whale and Arnoux's beaked whale included frequency-modulated whistles, burst-pulse clicks, and discrete clicks in rapid series. Other than these, only a few records of the acoustic behaviour of other species of beaked whale exist, and the majority of these were obtained from beach-cast or rehabilitated animals and so may not represent natural behaviour.

In the long term, the acoustic repertoire of beaked whales may allow researchers to find and identify animals at sea via the sounds they make. Such a technique will be particularly helpful for these species, which are difficult to find and identify visually. However, in order for this to be achievable, a comprehensive and accurate database of species-specific call types and structures needs to be established. This presents somewhat of a "catch-22" situation, as obtaining this ground-truthing data for beaked whales is extremely difficult, so progress on acoustic survey techniques for these species is limited.

Conservation

Their pelagic habitats and lack of concentrated populations have meant that most beaked whales have had little interaction with humans. The exceptions were the northern bottlenose whales in the North Atlantic and Baird's beaked whales in the North Pacific, both of which were quite heavily exploited in whale fisheries. Among the Antarctic beaked whales, only a few Arnoux's beaked whales and southern bottlenose whales have been killed during whaling for research purposes, and one Hector's beaked whale was apparently taken in the 1800s in New Zealand. Southern bottlenose whales have also been recorded as accidental victims of the driftnet fishery in the Tasman Sea.

The ecological role of beaked whales as top predators exposes them to increased levels of chemical pollutants. Cetaceans store energy (and pollutants) in their blubber, and have a lower capacity to metabolise some PCB isomers than many other mammals. Foreign and toxic substances are therefore often biomagnified as they move up the food chain. Toothed whales, which are usually quite high up their food chains, can have quite high levels, and even species such as beaked whales that live offshore and in relatively clean environments such as the Antarctic will be exposed to pollutants. High contaminant levels can have two major effects: (1) inhibition of the immune system's capacity to respond to naturally occurring diseases, and (2) potential reproductive failure.

There is also increasing concern about the effect of anthropogenic noise in the marine environment. Beaked whales appear to be particularly susceptible to the effects of low-frequency, high-intensity underwater sounds. Several beaked-whale stranding events have coincided with military naval exercises and the increased noise levels associated with these. It is unknown why beaked whales are particularly sensitive to such events, whether these are related to the deep-diving behaviour of these whales or the soft-tissue structure of their ears. However, regardless of the mechanism involved, caution needs to be exercised in terms of increasing sound levels in the habitats of these species. Increasing levels of underwater noise in the oceans are therefore currently a major concern for this group of animals.

Sascha K. Hooker

See also **Adaptation and Evolution; Biodiversity, Marine; Circumpolar Current, Antarctic; Convention on International Trade in Endangered Species of Wild Flora and Fauna (CITES); Diving—Marine Mammals; Fish: Overview; Food Web, Marine; Polar Front; Squid; Whales: Overview; Whaling, History of**

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BELGIAN ANTARCTIC *(BELGICA)* EXPEDITION (1897–1899)

In 1895 the Sixth International Geographical Congress in London passed a resolution to the effect that the Antarctic was the most important remaining field for geographical exploration. Remarkably, the first country to respond to this call was Belgium, a country with no significant recent maritime tradition and no earlier history of polar exploration. The person responsible was a young Belgian naval officer, Adrien de Gerlache de Gomery. Early in 1895 he had submitted his plans for an Antarctic expedition to the Royal Belgian Geographical Society; they were readily approved and a public subscription was opened. The proposed expedition received the patronage of HRH Prince Albert, and the government contributed 100,000 francs. In July 1896, de Gerlache bought the former Norwegian whaler *Patria,* a three-masted bark with an auxiliary steam engine of 35 hp; she was renamed *Belgica*. De Gerlache's stated plans did not initially envisage the ship wintering.

The expedition personnel represented an interesting mix of nationalities. The scientists included two Poles, Henry Arçtowski and Antoine Dobrowolski; a Belgian, Emile Danco; and a Romainian, Emile Racovitza. First Officer was a Belgian, Georges Lecointe; second officer was a Norwegian, Roald Amundsen, later to become one of the most famous polar explorers; third officer was a Belgian, Jules Melaerts. The medical officer was an American, Dr. Frederick Cook, who joined the ship at Rio de Janeiro on its way south. The crew consisted of Belgians and Norwegians.

Belgica put to sea from Antwerp on August 16, 1897, and from Ostend a week later. Having called at Funchal (Madeira), Rio de Janeiro, and Montevideo, she reached Punta Arenas on December 1. Naturalist Racovitza traveled to Punta Arenas independently, ahead of the ship. From there he made an extended collecting trip inland on horseback. Having penetrated as far as Lago Sarmiento and the Cerro Paine, he rejoined Belgica at Punta Arenas on December 3.

Belgica next called at the Argentine government coal depot at Lapataia on Canal Beagle, Ushuaia, the Reverend Bridges' estancia at Harberton (where it ran aground and was refloated only with great difficulty), and the penal colony at San Juan on Isla de los Estados. Thus it was not until January 14, 1898, that *Belgica* started south across the Drake Passage. The passage took the expedition between Snow and Smith islands in the South Shetlands on January 20, and to the east of Low Island on the 22nd, when a storm broke. While trying to clear blocked scuppers, a seaman, Karl Wiencke, fell overboard and was drowned.

Pushing south into Hughes Bay, de Gerlache next headed southwest into the wide strait (now named after him) between Liège, Brabant, and Anvers Islands and the Antarctic mainland. Over the next three weeks *Belgica* cruised among the complex scattering of islands in this strait, many of which still bear names bestowed by the expedition. A remarkable twenty landings were made by boat, while the islands were surveyed and the geology, flora, and penguins were studied. De Gerlache and Danco made a week-long sledge trip on Brabant Island, the first such scientific excursion in the Antarctic.

Running south through Neumayer Channel to Bismarck Strait and Flandres Bay, after passing Cape Renard and Lemaire Channel, De Gerlache continued south, crossing the Antarctic Circle on February 15. On the 16th, Adelaide Island was sighted, and Alexander Island soon afterwards. On February 28, relatively loose pack ice to the south offered the possibility of penetrating in that direction. Arguing that James Ross had found the open waters of the Ross Sea south of a significant belt of pack ice, and anticipating that the same situation might exist in the Bellingshausen Sea, de Gerlache headed south into the pack, although aware of the risk of becoming beset for the winter. That possibility became a reality on March 2, 1898, at 71°30′ S, 85°16′ W.

The upper deck was partially housed in with canvas, and the ship banked with snow for insulation. Accommodations were reorganized to save fuel. Huts and snow-houses for scientific investigations sprang up on the ice around the ship and a complex program of observations began in the areas of meteorology, oceanography, biology, and magnetic studies.

The sun was last seen on May 17. The ship drifted with the ice in complex loops and zigzags, but generally in a westerly direction, roughly along the 70° S parallel. By mid-winter, scurvy was affecting most of the ship's company, including de Gerlache. Cook managed to combat the disease by a diet of seal and penguin meat. But he also had to contend with mental illness. One of the Norwegian seamen developed a severe persecution complex. He began sleeping in obscure corners all over the ship, and on one occasion disappeared from the ship and was only found out on the ice after a protracted search.

Quite early in the wintering Emile Danco, who had been suffering from a heart complaint for some time, was forced to give up his studies of magnetism, and soon afterwards he took to his bunk. He died on June 5, 1898, and was buried through a hole in the ice 2 days later.

The sun returned on July 21, but breakup of the ice was still a long way off. In January 1899, work began on cutting a channel towards an area of open water some 600 yards (545 m) away. But after a month of laborious toil, the ice moved and the channel closed. Then on February 15 the ice opened again, steam was raised, and the ship reached a large polynya. It was not until March 14, 1899, however, that *Belgica* finally reached the open sea.

After being almost driven ashore during a gale, *Belgica* managed to enter the Canal Cockburn, and dropped anchor at Punta Arenas on March 28; she reached Antwerp on November 5, 1899.

Largely due to luck, the expedition had survived the first Antarctic wintering of any vessel. It had accumulated a vast amount of scientific data. The Belgica Commission, charged with publishing the expedition's results, ultimately issued ten volumes on almost every aspect of the expedition's work.

William Barr

See also **Amundsen, Roald; Bellingshausen Sea, Oceanography of; de Gerlache de Gomery, Baron Adrien**

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BELGIUM: ANTARCTIC PROGRAM

Belgian interest in Antarctica began in 1894 when Adrien de Gerlache unfolded his plans for a Belgian scientific expedition to Antarctica to the Société Royale Belge de Géographie and the Royal Academy. Although the ensuing *Belgica* expedition (1897–1899) was to a large extent privately funded, the impressive series of Résultats de voyage de la Belgica (sixty-five volumes) was commissioned and published by the Commission de la Belgica under the aegis of the Royal Academy.

The emphasis placed by the Special Committee for the International Geophysical Year (IGY) on the establishment of a geophysical network in Antarctica during the 1957–1958 IGY and the memory of the historical Belgica expedition convinced Belgium to join ten other countries and to establish a scientific station, Base Roi Baudouin, in Dronning Maud Land, a virtually unexplored part of Antarctica at that time. Twice for 3-year periods (1958–1961 and 1964–1966) this station fulfilled its role as a geophysical observatory and as an operating base for geographical, glaciological, and geological mapping of the neighboring coastal and mountain areas. After the closure of the base in 1967, three further summer expeditions were sent, but in 1971 all governmental support for Antarctic research was temporarily halted.

In 1985, the Belgian government took the initiative for a more structured approach with respect to its activities in Antarctica and started a series of multiannual scientific research programs managed by the Federal Science Policy Office. In this way Belgium could honor its obligations as a founding member of the Antarctic Treaty System, contribute to the knowledge required for conservation and management measurements of the Antarctic environment, and strengthen its research activities with respect to global environmental change. A call for research proposals was issued every 3–4 years among all university and federal scientific institute-based scientists, and the proposals selected on the grounds of a scientific assessment by foreign experts. The first three phases of the Belgian Scientific Research Program on the Antarctic (1985–1988: 2.3 million Euro; 1988–1992: 2.4 million Euro; 1992–1996: 3.9 million Euro) covered research projects in the domains of "Marine Biogeochemistry and Ecodynamics," "Hydrodynamics and Marine Geophysics," and "Glaciology and Climatology." The fourth (1996–2000: 6.3 million Euro) and fifth (2000–2005) phases were launched under the umbrella of a Multi-Annual Support Plan for a Sustainable Development Policy. Phase four covered "Marine Biota and Global Change," "Dynamics of the Southern Ocean," and "Paleoenvironmental Records," and Phase five "Climate and Atmosphere" and "Biodiversity."

Following an external assessment of the Belgian Antarctic Program, the Council of Ministers in its meeting of February 2004 took the decision to establish a new scientific station on the occasion of the International Polar Year in 2007–2008. The design and prefabrication of the summer-only base would be assured by the private sector thanks to the support gathered by the International Polar Foundation (IPF, projected cost of 3.0 million Euros). For the management of the station, a yearly sum of 1.2 million Euro is provided. Both the management as well as the scientific program will fall under the responsibility of the Federal Science Policy Office. A site survey in December 2004 allocated the planned new base close to Utsteinen Nunatak at the foot of the Sør Rondane Mountains, 180 km south of the former Belgian Roi Baudouin Station.

HUGO DECLEIR

See also **Antarctic: Definitions and Boundaries; Antarctic Treaty System; Belgian Antarctic *(Belgica)* Expedition (1897–1899); de Gerlache de Gomery, Baron Adrien; International Geophysical Year**

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BELLINGSHAUSEN, FABIAN VON

The Baltic German Fabian Gottlieb Benjamin von Bellingshausen (other versions of his name are Thaddeus von Bellingshausen and Faddej Faddeevich Bellinsgauzen) was a Russian seafarer born on the Estate of Lahhetagge/Lahetaguse on the Island of Ösel/Saaremaa in the province of Livonia on 20 September 1779. He was the fourth child in the family of the infantry soldier Fabian Ernst von Bellingshausen and his wife Anna Catharina (born von Folckern). After the father's death in 1784, the family suffered financial pressures and moved to Arensburg/Kuressaare. Although his brothers were sent to study at traditional military schools, von Bellingshausen was sent to a naval academy, something that at that time had no major tradition in Russia. He studied at public cost at the Naval Cadet Corps in Kronshtadt (1789–1797). He was very much a mediocre student, finishing his studies among the bottom five of his course.

In 1795, von Bellingshausen was promoted to gardemarine, and in 1797 he finished the Cadet Corps, attaining the rank of midshipman. From 1797 to 1803 he served in the Russian Baltic Sea squadron. In 1803–1806, he participated in the first Russian circumnavigation of the earth under the command of Adam Johann von Krusenstern, sailing on the frigate *Nadezhda*. He was an excellent cartographer, and drew all the maps later published from the expedition. After the expedition, von Bellingshausen was promoted to captain-lieutenant, and from 1807–1810 he continued his service on the Baltic Sea. During the period 1810–1819, he sailed on several ships in the Black Sea. He improved considerably the sea charts of the eastern coast of the Black Sea based on his own observations (Russwurm 1870; Paatsi 2000).

On 24 April 1819, at the recommendation of Makar Ivanovich Ratmanov and von Krusenstern, von Bellingshausen was appointed the leader of the South Pole group and the captain of the sloop *Vostok* (the captain of the transport ship *Mirnyy* was Mikhail Petrovich Lazarev) of the Russian expedition to the North and South Poles. The main goals of the expedition were to improve the map of the southern part of the Pacific Ocean and to approach as close to the South Pole as possible, making new discoveries in the Antarctic Ocean.

Following the expedition (1821), von Bellingshausen was promoted to captain-commodore, and he served in the Baltic Sea as the commander of the 15th unit of the navy (1821–1826). During this period, he also arranged his expedition materials and compiled a manuscript of the travel account in Russian, which he submitted to a Department of Admiralty in 1824 (it was published in 1831) (von Bellingshausen 1945).

In 1826–1827, von Bellingshausen cruised in the Mediterranean Sea with in a squadron of two ships and was promoted to rear admiral. In 1828–1829, he participated in the Russian–Turkish War and in the attack on the Varna fortress as the leader of a naval guard unit. From 1830 to 1839, von Bellingshausen was the commander of the 2nd division of the Baltic fleet, following which, from 1839 to 1852, he served as the harbour master and military governor of Kronshtadt. In 1843, he was promoted to admiral, and in 1844, he was appointed a member of the Council of Admiralty. Von Bellingshausen contributed greatly to the development of the harbour and town of Kronshtadt. He succeeded in widening the harbour considerably, at the same time founding parks and encouraging other developments that helped turn the rough naval base into a city appropriate also for a civilian population (Korguev 1900). In appreciation for his efforts, the inhabitants of Kronshtadt later set up a monument of von Bellingshausen, which was opened in 1870. Von Bellingshausen died in Kronshtadt on 25 January 1852.

Personal data on Bellingshausen are scanty and rather contradictory—on the one hand, he was valued highly as a very conscientious and educated seafarer; on the other, his education was considered limited and he was thought superior and arrogant. None of his contemporaries, however, was doubtful of his abilities in cartography or his seamanship, the latter of which included a special study in how to aim at a target in the sea (Bellingshausen 1839). There are numerous geographical objects that have been named after von Bellingshausen: a hollow and an atoll in the Society Islands in the Pacific Ocean; a cape on Sakhalin Island and another on South Georgia; a sea in the Antarctic (named by Jean-Baptiste Charcot in 1908–1910); a coast on Peter I Øy; a shelf glacier, a mountain, and a Russian station in the Antarctic; and islands in the Aral Sea and in the South Sandwich Islands.

ERKI TAMMIKSAAR

See also **Charcot, Jean-Baptiste; History of Antarctic Science; Peter I Øy; Russian Naval (*Vostok* and *Mirnyy*) Expedition (1819–1821); South Sandwich Islands**

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BELLINGSHAUSEN SEA, OCEANOGRAPHY OF

Location

Named after Thaddeus von Bellingshausen, who led the Russian expedition to the south polar region in 1819–1821, the Bellingshausen Sea lies west of the Antarctic Peninsula at the southeast extremity of the Pacific Ocean. Situated between Alexander and Thurston islands, it lies north of Ellsworth Land and adjacent to the Amundsen Sea in the west. Due to its remote location and extensive sea-ice coverage, the region is relatively undersampled. The Russian expedition was followed by *Belgica,* which over-wintered in the ice (1897–1899), but only in the last two decades has interest developed with projects under the auspices of international programmes such as IGBP-JGOFS (Joint Global Ocean Flux Study), GLOBEC (Global Ocean Ecosystem Dynamics), and WCRP-WOCE (World Ocean Circulation Experiment). Much information has been obtained remotely by satellites, such as passive microwave measurements of sea-ice extent, sea-surface temperature from advanced very-high-resolution radiometers (AVHRR) and along-track scanning radiometers (ATSR), and surface chlorophyll from Coastal Zone Colour Scanner (CZCS) and sea-wide field-of-view sensor (SeaWiFS) satellites. Numerical modelling of the area has been included in regional and global ocean-circulation models.

Setting

The shelf width ranges from 100 to 450 km, with average water depths varying between 350 and 650 m. Ocean depths extend to 3500 m. Locally deep troughs are cut into the shelf. The upper continental shelf is steeper in the eastern Bellingshausen Sea (13°–17°) than in the west (1°–4°). The lower slope is cut by erosional channels extending across the continental rise down to the abyssal plains. Elongated sediment mounds, associated with the channels, rise 1000 m above the adjacent sea floor. Features such as Peter I Island and Marie Byrd Seamount are volcanic peaks. The region is volcanic in origin, formed by the subduction of Pacific oceanic lithosphere beneath the continental margin of Gondwana, with the break-up of Gondwana leading to movements of crustal blocks along the region. The Antarctic Peninsula and eastern Ellsworth Land form a deeply eroded magmatic arc with much of the shelf and islands formed of clastic and volcanogenic sequences. The ice cap of the Antarctic Peninsula is drained by valley and outlet glaciers into the eastern Bellingshausen Sea. Locally these coalesce to form ice shelves, whose flow is confined by the local topography, islands, and peninsulas.

Climate

The climate is determined by the Antarctic circumpolar atmospheric pressure trough lying north of the coastline, which is characterised by many deep depressions and generally brief anticyclonic episodes. The leading modes of climate variability are the Antarctic

Oscillation (AAO) and changes in the semiannual oscillation (SAO).

The AAO is the leading principal component of sea-level pressure south of 20° S. Most variability associated with the AAO is zonal, but a nonannular component can be found, with a low-pressure anomaly west of the Antarctic Peninsula for high values of the AAO index. The AAO has a clear and strong impact on the structure of the ocean currents over large parts of the water column. At the surface, transport anomalies associated with a positive phase of the AAO are directed toward the northwest at high latitudes (south of 45° S), inducing an upwelling that features a maximum at around 65° S and a downwelling at about 45° S, which is balanced by a southward return flow below 1500 m. The nonannular response of the AAO gives rise to a low-pressure anomaly in the Amundsen-Bellingshausen Sea sector during positive AAO years, when the Weddell and Bellingshausen seas are subject to more northerly winds, which induces a warming at the surface and a decrease in their ice-covered areas. The reverse is true of the Ross and Amundsen seas; hence, integrated over the Southern Ocean such regional differences cancel out.

The SAO is a twice-yearly contraction of the circumpolar pressure trough due to differences in energy uptake between Antarctica and its surroundings. It results in a half-yearly wave in baroclinicity and depression activity. Latitudinal sea-ice extent in the Amundsen and Bellingshausen seas fluctuates with the movement of the circumpolar pressure trough, so a weakly developed SAO suppresses sea-ice growth.

Sea Ice

The climate is strongly influenced by sea-ice extent. Synoptic scale weather patterns, air temperatures, and the regional atmospheric circulation are all affected by the extent of sea ice.

The annual cycle of sea ice cover in the Bellingshausen Sea is unusual in its symmetry between ice growth and retreat. The more typical Southern Ocean cycle is one of slow growth and rapid retreat. Since rapid retreat in spring exceeds the available air–sea heat flux, the heat deficit must be made up from the underlying deep water. A more gradual retreat in the Bellingshausen Sea implies less deep-water influence, consistent with a relatively low-salinity surface layer. The Amundsen and Bellingshausen seas also exhibit a low seasonal range in sea-ice extent compared to other sectors of the Southern Ocean. Sea ice is sensitive to changes in atmospheric circulation and the frequency, depth, and track of depressions in and to the north of the circumpolar pressure trough. When depressions are slow moving and there is persistent meridional wind, large sea-ice anomalies may become established and can persist for several seasons.

Exceptional sea-ice retreats and advances occur in the Bellingshausen Sea, including sea-ice retreat during winter. It is usually associated with a combination of enhanced poleward flow and warm-air convection. The winter of 1993 was remarkable for the amplitude of excursions in the sea-ice edge. The changes were so pronounced because of the strong meridional winds induced by strong high–low pressure couplets on either side of the Antarctic Peninsula and the marked changes of near-surface temperature they brought about, which fluctuated rapidly. The rapid melting and refreezing of ice led to extensive movements in the ice edge.

Strong feedback between temperature over the Antarctic Peninsula and sea-ice cover in the Amundsen and Bellingshausen seas is at least partly responsible for anomalous warming of this region in the last 50 years. A major decrease in sea-ice extent in the Bellingshausen Sea began in the late 1980s. The retreat was correlated with increasing surface air temperatures on the west coast of the Antarctic Peninsula and coincided with more northerly surface winds and greater cyclonic activity. The last 2 decades have been the warmest in the last 5 centuries. During that time, the occurrence of the minimum extent of sea ice moved from March to February. The ice retreat, which was first observed in summer, now extends through all seasons, and the mean latitude of the Amundsen and Bellingshausen ice edge has shifted southward by about 1.5° latitude per °C temperature.

Oceanography

The Bellingshausen Sea lies in the Antarctic Zone of the Southern Ocean, where the ocean circulation is dominated by the wind-driven, eastward-flowing Antarctic Circumpolar Current (ACC). While the main part of the current passes to the north, the broadening of the flow as it crosses the Southeast Pacific Ridge brings the southern ACC boundary into the Amundsen and Bellingshausen seas. The Antarctic Zone comprises the flow between the core of the ACC at the Polar Front and the southern ACC boundary. The zone south of the ACC lies between the southern ACC boundary and the coast. Prevailing easterly winds south of 65° S drive a westerly to southwesterly flow of water, but the current regime is complex, with meanders and cyclonic gyres and no dominant pattern of flow.

Water masses upwell along isopycnals within the ACC, bringing warm, saline Circumpolar Deep Water (CDW) toward the sea surface. There is no marked front along the shelf break, allowing CDW to upwell onto the continental shelf where it causes intense melting at the base of the ice shelves. Limited observations confirm the lack of shelf water in the Bellingshausen Sea, one of the two prerequisites for the formation of bottom water. Thus, production of cold, dense water that sinks beneath CDW is unlikely. Rather, bottom water formed in the Ross Sea is circulated cyclonically around the deep southeast Pacific to reach the Bellingshausen Sea in modified form. Modified deep water from the Weddell Sea spreading westwards around the tip of the Antarctic peninsula may spread further westwards in a narrow, weak bottom current observed on the continental slope. The surface layer consists of cold ($<-1.5°C$), low-salinity Antarctic Surface Water.

Biogeochemistry

The upwelling of CDW across the southern ACC boundary provides a nutrient-rich input to the upper layer of the water column. Nutrient concentrations below 100 m are consistently high. In the surface layer, nutrient concentrations reflect recent biological activity; for example, in late spring, nitrate, phosphate, and silicate decrease from south to north while nitrite, ammonium, biogenic silica, and chlorophyll increase.

Micronutrient measurements are few. Observations of dissolved iron show low levels, while the range of values includes the lowest measurements made in the Southern Ocean. Some enhancement of iron concentrations occurs to the north of the Polar Front and towards the Antarctic continent, where deeper waters may be affected by input from the continental margin sediments.

The Bellingshausen Sea acts as a sink for atmospheric carbon dioxide during summer, probably due to biological activity. Periods of increased uptake of carbon dioxide may be caused by enhanced productivity or changes in circulation, and demonstrate that the area has the capacity for rapid and large changes in carbon uptake.

Marine Flora and Fauna

A major feature of the Bellingshausen Sea is its paucity of marine fauna. Satellite observations show the remote southeast Pacific to be unproductive, with little algal biomass, which is undoubtedly linked to the relatively low numbers of zooplankton and higher predators such as cetaceans and seabirds.

Exceptional blooms of phytoplankton occur in inshore waters and in offshore waters associated with the marginal ice zone. However, a classical ice-edge bloom, stabilised by melt water from retreating ice, has not been observed *in situ*. Rather, enhanced productivity is associated with frontal zones to the south of the ACC. Macronutrients are not limiting, but low levels of dissolved iron are, and iron stress limits all sizes of phytoplankton. Composition of the phytoplankton community varies with the dominant water masses reflecting nutrient characteristics; in particular, diatoms are restricted to silicate-rich waters south of the Polar Front.

Only the abundance of bacteria and protozoa (microzooplankton) is higher in the Bellingshausen Sea than other regions. The under-ice community is dominated by bacteria where phytoplankton are minimal, but their importance diminishes away from the ice, where phytoplankton increase in importance. High-standing stocks of protozoa in the marginal ice zone are important in that they exert a significant impact on phytoplankton, grazing in excess of 100% of the phytoplankton population. Through exerting a continuous high grazing pressure, protozoa are more important than krill, which have a localised, episodic impact.

The abundance and biomass of zooplankton in the Bellingshausen Sea are among the lowest recorded for the Antarctic. Copepods dominate numerically, but species vary from year to year through variability of ice conditions. In warmer years with less ice, then, salps can show a dramatic increase in biomass. Sea-ice conditions between the Bellingshausen Sea and Antarctic Peninsula region are closely linked, which would support similarities within the krill stock composition between the two regions.

Cetaceans, mainly minke and humpback whales, tend to be associated with the ice edge and coastal habitats and are found in the greatest numbers when the sea-ice boundary is located over the shelf edge. Although humpback whales are migratory, individuals have been observed during austral winter in shelf areas of the Bellingshausen Sea. Krill predators other than whales are also found in higher abundance in the same area as whales. Seabird density is similar to other continental shelf areas but significantly lower than the Ross Sea. Birds are more abundant near ocean frontal zones, the ice edge, and the shelf break, either because habitats of different species overlap, as at frontal zones, or because processes in the region, such as the shelf break, concentrate the variety of prey (zooplankton, fish, squid) eaten by Antarctic seabirds.

JANE F. READ

See also **Amundsen Sea, Oceanography of; Antarctic Bottom Water; Antarctic Peninsula; Antarctic Surface Water; Belgian Antarctic *(Belgica)* Expedition (1897–1899); Bellingshausen, Fabian von; Circumpolar Current, Antarctic; Circumpolar Deep Water; Climate; Copepods; Gondwana; Humpback Whale; Marginal Ice Zone; Minke Whale (Antarctic Minke Whale); Peter I Øy; Polar Front; Remote Sensing; Ross Sea, Oceanography of; Russian Naval (*Vostok* and *Mirnyy*) Expedition (1819–1821); Scotia Sea, Bransfield Strait, and Drake Passage, Oceanography of; Sea Ice, Weather, and Climate; Seabird Populations and Trends; Southern Ocean; Southern Ocean: Fronts and Frontal Zones; Teleconnections; Whales: Overview; Zooplankton and Krill**

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BENTHIC COMMUNITIES IN THE SOUTHERN OCEAN

On land and on the shore, Antarctica seems a barren land, with transient penguins and seals being the most striking examples of life. For most of the year the sea is measurably the clearest in the world; there may be masses of krill, comb jellies, and salps in the water, but these are few in species. Life on the sea bed could not be a greater contrast; below the shallows, which are scoured by the abundant small icebergs, the rocks are densely covered by a rich variety of colourful animals. On sediments too there are a wide variety of organisms, from ancient and massive sponges to burrowing bivalve molluscs, scavenging amphipods, and predatory seastars.

For decades this secret world has been accessible mainly just to scientists working from Antarctic bases, but tourist vessels are increasingly gaining the capacity to glimpse the bottom by using Remote Operated Vehicles (ROVs) or SCUBA diving. Perhaps the most striking feature to a viewer would be how little life there appears to be in the shallowest water and how rapidly this increases to coral reef–type densities and diversities by 25–40 m. This is because of ice scour (and, at very high latitudes, anchor ice). The sea bed in the shallowest water is permanently in a state of recolonisation from the scraping and gouging action of icebergs. With increasing depth, therefore, the communities tend to be older on average and succession can be seen from the weedy pioneers (such as bryozoans, stalked ascidians, and hydroids) to the longer-lived and slow-growing volcano sponges. Experimental settlement panels have been put out in shallow water by marine biologists at various locations around Antarctica to investigate how quickly animals colonise and how rich these early communities are. The results have been quite varied, some showing very slow rates of recolonisation and some (such as at McMurdo Sound) suggesting long periods of years when little settles followed by a brief major pulse in recruitment. Another highly visual and striking feature is how few organisms are moving—most of the benthos is sessile (nonmobile), and even the mobile scavengers and predators are in no rush. Viewing the same site a week later can reveal sea slugs (nudibranchs), sea spider (pycnogona), nemertean worms, or other predators still in the same place eating the same meal. This is life in the slow lane. The tick-over (metabolism) and growth of the Antarctic invertebrates measured to date is slow. A dominant lifestyle is suspension feeding, so the observer in summer would see a crowded mass of tentacles from (polychaete) worms, bryozoans, hydroids, sea cucumbers (holothurians), brittle stars (ophiuroids), and basket stars (crinoids) straining plankton from the water. Ascidians (sea squirts), sponges, brachiopods, and other peculiar animals (such as Entoprocts) would be doing the same but less, obviously, and without tentacles.

Their food is, like the light climate, very seasonal. For a few months a year (December–February) there is a very intense phytoplankton bloom, typically dominated by tiny diatoms. Many of these suspension feeders (often referred to as "filter feeders") eat even smaller organisms in the water called ciliates, flagellates, or even bacteria. It was thought for a long time that such animals would have to hibernate for most of the year and resume activity during the brief polar summer, but it now appears there are a great variety of strategies. Some species even feed all year round—on what, though, is a mystery. Other aspects of their environment are also very seasonal—it is not so obvious, but the sea temperature rises dramatically in the summer from around freezing (just below –1.8°C) to just above freezing briefly. This may not seem much but, as on coral reefs, the upper summer temperatures are close to the thermal limits for many species. At just 2°C, some animals may have their ability to function normally severely affected and at 5°C many may die (they are very steno-thermal). At some localities, such as McMurdo Sound (Ross Sea) and Ellis Fjord (East Antarctica), the benthic communities live in the most thermally stable environment known on earth. Being cold and well mixed, the water holds gas very well, and the high oxygen concentrations have enabled some organisms (sea spiders, amphipods, and isopods) to attain giant sizes. Paradoxically, other groups, such as many molluscs, are very small. A common feature of polar benthos (Antarctic and Arctic) is great longevity: some brachiopods, bivalve molluscs, and sponges may live to 100 years old or more.

Even on most coral reefs it would be hard to see as many different types of animal in any particular spot. It is frequently stated by biologists that there is a global (bio)diversity cline (a decrease of species from tropics to poles). There is much supporting evidence for this idea in the Northern Hemisphere seas, but in the Southern Hemisphere the sea bed around Antarctica is very species rich (in contrast to impoverished Arctic sea beds). Thus, patterns of richness strongly differ between hemispheres because of the difference between how many species live in the north versus south polar sea beds. The richness in Antarctic waters is not evenly distributed either by geography or between animal types. To date, particularly high numbers of benthic species have been found in the Scotia Arc, the Weddell Sea, and the Ross Sea. Comparisons are difficult though, because these areas have been well sampled, whereas others, such as the Amundsen Sea, have only rarely been visited. Some types of animals, polychaete worms, sea spiders, and a few other groups, have a much higher proportion of the world's species than would be predicted on the basis of habitat (continental shelf) areas. Why should this be? It is likely to be a combination of factors, but compared to the Arctic, for example, the sea bed around Antarctica is very old. But the animals around Antarctica are not just unusual because there are lots of them; it is that most of them occur nowhere else. Between 70% and 90% of species from most groups of animals are endemic (only occur there). There are, of course, some exceptions, but also the macro-algae in Antarctic waters are a subset of those north of the Polar Frontal Zone (PFZ) and thus occur in, for example, Patagonia. For the most part, though, there is an abrupt change in the fauna across the PFZ—the animals living at South Georgia are very different to those of the Falkland Islands and Patagonia.

Despite the high levels of richness, the observer of the ROV pictures or using SCUBA would come across many of the same animals in the shallows almost wherever they went around the Antarctic. Certain species are particularly ubiquitous and many even seem circumpolar. The limpet, *Nacella concinna,* the burrowing clam, *Laternula elliptica,* the giant yellow nemeratean worm, *Parbolasia corrugatus,* the bright red sea urchin (echinoid) *Sterechinus neumayeri,* the red sea star, *Odontaster validus,* and the stalked ascidian, *Molgula pedunculata,* are examples. The west wind drift and Antarctic Circumpolar Current (ACC) may aid such distributions by carrying larvae around the margins of Antarctica, although new investigations of cryptic speciation (species which look morphologically similar but which are genetically different) may reveal that there are many fewer circumpolar species than are currently thought. It is notable that within many major groups of animals many Southern Ocean species brood their young but also that the most abundant species do not. In some groups, brooders have had greater evolutionary success (generation of many species) but those with planktonic larvae have had greater ecological success (more abundant and ubiquitous). It has been theorised that the alternating conditions of ice sheets bulldozing the fauna to the deep edges of the continental shelves during ice ages followed by rapid retreats in interglacials may be responsible for such a pattern. Certainly the species with long-lived planktonic larvae (broadcast spawners) would seem to have a strong potential to rapidly recolonise the empty sea bed after each ice sheet retreats. In recent time our current picture of the rich benthos fighting for space on the shallow Antarctic sea bed is not really a "normal" one: in the last 430,000 years ice sheets have covered the land and sea (as during ice ages) 90% of the time.

Some scientists believe the benthic communities around Antarctica are the oldest in the world; they are certainly quite different in character and behaviour to those anywhere else. To date, they, together with the deep abyssal plains and trenches, are probably the environment least influenced by man.

The whaling and sealing must have made tremendous changes to the functioning of the pelagic ecosystem in Antarctica, as fishing has disastrously for coastal ecosystems elsewhere. Much of ice-free Antarctica has also been dramatically altered indirectly or directly by human activities, most notably in the form of recent invading species. The benthic communities of Antarctica have experienced a warmer period before, but it seems likely they face rapid warming, accelerating melting and collapse of ice shelves, and invaders clinging to the hulls of ships. In shallow water Antarctica's benthos can be considered to represent a last frontier, but their resilience to crushing from massive icebergs and to the bulldozing of ice ages may be tested much more severely if some of the predictions of current climate-change models become reality.

David K. A. Barnes

See also **Antarctic Circumpolar Current; Copepods; Deep Stone Crabs; Gigantism; Growth; Molluscs; Polar Front; Seaweeds; South Georgia; Zooplankton and Krill**

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BIODIVERSITY, MARINE

Biodiversity can be defined as the collection of genomes, species, communities, and ecosystems in space and time. In the Antarctic marine environment it expands from surface-water and ice-algae assemblages over phytoplankton and zooplankton down to benthic assemblages. Knowledge of biodiversity of geographic areas is essential for conservation: species, assemblages, and communities can only be assessed for their importance or protection requirements. Large-scale patterns of biodiversity feed and underpin theoretical ecology and paleoecology once they have been recognised. Biodiversity means ecological diversity, genetic diversity, and whole-organism diversity. The population is the unit of organisms that fundamentally links these components. On the background of the Antarctic Treaty, knowledge of biodiversity is crucial for all marine and terrestrial habitats of Antarctica.

The most fundamental step to biodiversity research is the accurate recognition of specific taxonomic levels (usually species) and classification of variation within these and of assemblages. Such information is essential for identifying patterns of biodiversity and for understanding how these patterns change over space and time. A visitor walking Antarctica's coast would see that most of the coastline is ice shelf, but even shores away from the ice shelves seem barren of life. Yet new research is revealing that even here in this ice, wave, and ultraviolet light–hammered habitat there is considerable biodiversity. Below the surface, snorkellers, SCUBA divers, or surface watchers of Remote Operated Vehicle cameras (ROV) would see a very patchy environment. There are sheltered areas that teem with benthic life but much of the shallows is criss-crossed with gouge marks from previous ice scours. Nevertheless, shallow boulder fields may have levels of richness equal to or higher than those in southern Patagonia. The biodiversity in any one place may depend most on when it was last crushed by icebergs, and thus how long it has had to recover. Similarly, but on a larger scale in time and space, the biodiversity of continental shelves in Antarctica at any one point in time will be linked to the last time ice ages (glacial maxima) scraped away most of the fauna and how much time they have had to recover (in interglacial periods, such as the present time).

Our understanding of the biodiversity of the past depends on the quality of palaeontological data. The vast majority of biologists are interested in the biodiversity of the present and believe in a biodiversity crisis caused by species becoming extinct at an alarming rate; our estimates of future biodiversity depend on sound modelling of data from the past and present. The present-day biodiversity of the Southern Ocean marine faunas has been strongly influenced by continental drift, the subsequent change of the hydrography and the paleoseaways, regional and global climate change, dispersal capabilities of the organisms, physiological adaptations, and the zoogeography and evolution of the species, which result from this geological framework. Plate tectonics, palaeoceanography, and the subsequent development of the Antarctic Circumpolar Current (ACC) and the psychrosphere fuelling the cold world's deep-sea bottom water (which is linked to the surface water) have enhanced successive cooling and glaciation of Antarctica. This cooling was probably a key event for the evolution of many Antarctic marine taxa.

A remarkable oxygen and carbon isotope change occurred in Antarctic waters about 57 Ma, indicating rapid global warming and oceanographic changes that caused one of the largest deep-sea benthic extinctions of the past 90 million years. In contrast, the oceanic plankton were largely unaffected, implying a decoupling of the deep and shallow ecosystems. There are three hypotheses for the deep-sea benthic crisis: (1) a rapid warming of the deep ocean in bottom water sources; (2) a deep-sea oxygen deficiency due to the sudden warming and change in circulation of deep water; (3) a sharp drop in surface ocean productivity that reduced trophic resources available for deep-sea benthic organisms.

In the 1970s, it was postulated that marine biodiversity is higher in the deep sea than on the shelf or on the continental slope, and a number of hypotheses have been used to explain high deep-sea species diversity. These include, for example, the stability–time hypothesis (maintenance of environmental stability characterizes the deep sea and leads to the development of a highly diverse community), and the biological disturbance theory describing processes of contemporaneous disequilibria (habitat change or heterogeneity and biological disturbance in terms of interspecific and intraspecific interactions lead to faunal diversification). Predation and competition are also disequilibrium explanations of high species diversity, which might be as important as productivity (food availability and/or dietary specialization).

Numbers of Species Known for Selected Southern Ocean Taxa

Phylum	Taxon Name	Number of Species
Macroalgae	Rhrodophyta	75
	Phaeophyta	26
	Chlorophyta	17
Porifera	Demospongiae	182
	Calcarea	14
	Hexactinellida	29
Cnidaria	Hydrozoa	155
	Alcyonaria	28
Arthropoda/Crustacea	Amphipoda	>800
	Isopoda	>600
	Cumacea	~123
	Mysidacea	59
	Tanaidacea	~110
	Ostracoda	323
	Decapoda	37
	Cirripedia	50
Arthropoda/Chelicerata	Pycnogonida	180
	Nemertea	30
Sipunculida	Sipunculida	16
Echiurida	Echiurida	9
Annelida	Polychaetes	645
	Pogonophora	3
Mollusca	Bivalvia	123
	Gastropoda	497
	Cephalopoda	34
	Scaphopoda	10
	Aplacophora	>25
Tentaculata	Bryozoa	281
	Brachiopoda	19
Echinodermata	Ophiuroidea	119
	Asteroidea	108
	Echinoidea	74
	Crinoidea	28
	Holothuroidea	106
Tunicata	Ascidiacea	118
Pisces	mostly Notothenioidei	208

Updated from Clarke and Johnston 2003.

Productivity is directly dependent on solar energy, and this is, of course, much lower at the poles than in the tropics. Productivity, climatic variations, and size of the habitats are some causes being discussed as potential reasons for global latitudinal gradients in species biodiversity observed for many taxa from shelf to deep-sea environments. These theories still have to be tested for the Southern Ocean deep sea, because as of the mid-2000s only about forty stations were sampled during the ANDEEP expeditions.

There are a number of large-scale Southern Ocean currents, fronts, and water masses that are notable in connection with biodiversity. Today, the Southern Ocean is isolated by the Polar Front (sometimes called the Antarctic Convergence). The Polar Front is the strongest jet of the ACC and the northern limit of the cold surface-water masses. Antarctic Bottom Water (AABW) is generated at the Southern Ocean ice margins; it is cold and highly saline, and it led to the isolation of the benthic faunas when, in the Oligocene/Miocene, temperatures decreased. Its high density causes the sinking of this water mass down the continental shelf and slope into the Southern Ocean deep sea, where it carries oxygen to the deep-sea basins of the other world oceans. From sampling the Southern Ocean deep sea, we can postulate that the Southern Ocean deep-sea fauna are not isolated and share faunal elements with other deep-sea basins further north. Deep-water Antarctic organisms may also have strong connectivity with the shelf fauna as well, due to the absence of a thermocline and similarity of some physical conditions in shallow and deep waters.

During the gradual physical isolation of the Antarctic continent from the Late Cretaceous to the early Cenozoic, the "Weddellian Province" was established and characterised by a number of distinctive epifaunal taxa. This fauna was affected by the mass extinction event in the Late Cretaceous, but some (e.g., benthic Mollusca) crossed the K-T boundary in Antarctica. The successive cooling, glaciation, and isolation of the continent had a strong influence on the evolution and radiation of many Antarctic marine taxa and shaped the evolution of many key elements of the present-day benthic marine fauna. Notothenioid fish, peracarid crustaceans, polychaete annelids, and pycnogonids radiated in the Southern Ocean, resulting in a high biodiversity of these taxa. Molecular evidence dates the radiation of the Notothenioidei to the Middle Miocene. A key physiological and evolutionary acquisition of the Notothenioidei is the antifreeze glycopeptides in their blood, a development coincident with the onset of the temperature drop and freezing seawater. Moreover, the extinction of most decapod crustaceans and bony fishes (Teleostei) caused the emergence of new ecological niches previously occupied, and this process might have opened opportunities for spectacular adaptive radiations, like for the brooding peracarid crustaceans. Molecular systematics has revealed that the numbers of species in the Southern Ocean (as in many other regions) are probably underestimated because of the existence of cryptic species that cannot, or cannot easily, be differentiated morphologically.

Radiations of species result from the evolution in isolation over long periods of time. Taxa that have radiated are therefore often characterised by high degrees of endemism (60%–90% in bryozoans, peracarid crustaceans, and notothenioid fish). The cooling of the Southern Ocean from the late Cretaceous is likely to have particularly influenced sensitive early life-history stages. This would suggest that species with larval stages might have had selective disadvantages and brooding was favoured. Certain types of echinoid (sea urchins) and peracarid crustaceans provide evidence of this. Peracarids, for example, have a marsupium and exhibit brood protection, which reduces the migration potential of offspring. This may have helped local speciation and finally led to adaptive radiations which have been described for the Epimeriidae and Iphimediidae (Amphipoda) or Antarcturidae and Serolidae (Isopoda) on the Southern Ocean shelf, and for the asellote isopod family Haploniscidae in the Southern Ocean deep sea.

Although brachyuran crabs and balanomorph barnacles are absent from the Southern Ocean benthos, eleven species of lithodids have been reported south of the Polar Front, and anomuran and brachyuran larvae have been reported from the Bransfield Strait of the Antarctic Peninsula. The absence or scarcity of these higher predators from the Antarctic shelf ecosystem may well have favoured the evolution of the peracarid crustaceans. However, the recent records of anomuran lithodid crabs in the Southern Ocean deep sea of the continental slope raise the question of whether crabs are returning to the Antarctic after their extinction in the Lower Miocene (15 Ma) and possible consequences of such a return for benthic communities. Potential factors underlying crab transport and establishment in the Southern Ocean range from travelling in ocean eddies and hitching a ride on ships (perhaps in ballast water), to regional warming changing survivorship levels.

We have to assume that many shelf species can physiologically tolerate life at greater depths. It has been demonstrated that larvae of Sterechinus neumayeri might be extremely temperature and pressure resistant. It is, however, unknown whether the development of the deep-water production influenced the migration potential larvae in general and thus enhanced submergence of some species.

The present-day Southern Ocean biodiversity is the result of different and simultaneously occurring biogeographic and evolutionary processes. These include the progressive retraction of taxa of a former cosmopolitan distribution established during the Jurassic and Cretaceous periods, of disjunct distributions of genera or species due to continental drift vicariance, active migrations of taxa in and out of the Southern Ocean, and radiation events due to the emergence of new adaptive zones. Whatever the true causes are for the biodiversity observed, the Islands of the Scotia Arc, the sub-Antarctic Islands around the Antarctic Peninsula and the western Weddell Sea have been identified as centres of high biodiversity, and the Gunnerus and Astrid Ridge, for example, as areas of lower biodiversity.

Rates of species description for many Southern Ocean taxa show no sign of approaching asymptote (tailing off).

The most speciose taxa of the Antarctic benthos are the Polychaeta, Gastropoda, Bryozoa, Amphipoda, Isopoda, and Porifera. Sessile taxa are certainly well represented. Many other epifaunal taxa appear to have adapted well to the coarse-grained glacial substrates, as in many areas on the Antarctic shelf suspension feeders are especially prominent. Dense communities of sponges, ascidians, anemones, hydroids, gorgonians, bryozoans, and crinoids are characteristic of the modern Antarctic shelf fauna below the zone of the influence of ice scour and anchor ice formation. This fauna often forms stratified communities of three-dimensional shape (as seen in coral reefs and tropical rain forests). Associated with these sessile forms are errant and vagile taxa such as echinoderms (ophiuroids, asteroids, echinoids, and holothurians), pycnogonids, isopods, amphipods, nemerteans, and gastropods. Polychaetes are speciose in the Southern Ocean, occurring with more than 600 species, and peracarid crustaceans have radiated. It is thought that the adaptive radiation of some families of the Amphipoda (e.g., Epimeriidae, Iphimediidae) and Isopoda (Antarcturidae and Serolidae) is due in part to the extinction of many of the decapod crustaceans in the Southern Ocean. However, possible radiation processes resulting in complexes of rather similar species have recently been described for the Southern Ocean deep sea.

In general, the species composition of abyssal deep-sea communities is poorly known in comparison with shelf and upper-slope environments. The extent to which deep-water fauna depend on biotic versus abiotic parameters, their speciation processes, and their regionalisation is even more poorly understood. Species diversity and benthic community patterns may vary tremendously between deep-sea habitats. Explanations of such variability in deep-species biodiversity have suggested depth, latitude, or sediment-structure influences. Theories such as latitudinal gradients in species diversity are hotly debated in science, but the basis for these arguments is still weak, as vast areas of the deep sea, especially of the Southern Hemisphere, remain unexplored.

Some Southern Ocean deep-sea genera have eyeless species or species with rudimentary eyes, whose phylogenetically related shelf species possess well-developed eyes and are endemic to the Southern Ocean. It seems probable that these deep-sea species (e.g., Serolidae and Antarcturidae isopods) descended into the deep sea from shelf ancestors with highly developed eyes. Other eyeless isopod species are representatives of families that have lived in the deep sea for long periods of time. These have probably developed in the deep sea *in situ,* where they possibly also radiated before they ascended onto the continental shelves, especially at higher latitudes because of the absence of a thermocline (e.g., the asellote isopod families, Munnopsididae and Haploniscidae).

The wider bathymetric distribution of Antarctic invertebrates (when compared to other seas) suggests that eurybathy might be a result of the physical changes of the continent due to the dynamic climate changes of the neogene resulting in alternating phases of glaciation and deglaciation. The heavy weight of the ice cap is generally regarded as the prime reason of the fact that the Antarctic shelf is usually much deeper than those of other continents. The subsequent changes in the ice-shelf extension probably also led to speciation processes on the Antarctic continental shelf, and in some taxa even to adaptive radiations. For this reason some authors refer to Antarctica as an "evolutionary incubator." It is unknown to what extent species have migrated up and down the Antarctic continental shelf and slope following ice extensions and retreats during glacial maxima and minima. This possible biological consequence of climate changes might also alternatively have led to the high eurybathy of many Southern Ocean species seen today. Crucially, the fauna, being pressure tolerant, may have migrated up and down the Antarctic continental shelf and slope in the past or in and out of abyssal plains of other world oceans.

The Antarctic Deep Water (ADW) production plays a crucial part for the deep-sea Isopoda for colonising the deep sea of the world oceans. It might serve as some sort of a diversity pump, though to what extent remains unclear. It is possible that the ADW production in the Weddell Sea acts as a distribution mechanism, enhancing the migration potential of species, driving Antarctic deep-water fauna northwards into the Atlantic Ocean over evolutionary time scales. In this respect, the Weddell Sea may be an important source for taxa presently living in the Atlantic and other neighbouring parts of the deep oceans. This assumption is underpinned by the more-or-less isothermal water column of the Weddell

Sea, and the surroundings of the Antarctic continent provide an obvious conduit for the migration of shallow-water species into the deeper waters.

The Antarctic shelf is well isolated from the shelves of the former Gondwana continents and therefore serves as a beautiful evolutionary laboratory. On the contrary, the deep-sea fauna are not isolated, and huge areas surrounding the Antarctic continent are deep sea, and our knowledge of the Southern Ocean deep-sea fauna is scarce. Recent Southern Ocean benthic deep-sea biodiversity studies (ANDEEP) have been aimed at the conduction of the first baseline survey of the deep-water benthic faunas of all size classes from meiofauna to megafauna of the Scotia and Weddell seas.

Within the meiofauna, three groups are very abundant in the Southern Ocean deep sea. These are the Foraminifera (protistan meiofauna), Harpacticoida (copepods), and Nematoda (worms). Recent deep-sea foraminiferan biodiversity research has particularly focussed on the diverse and usually neglected soft-shelled species (e.g., allogromiids, saccamminids, and komokiaceans), the vast majority of which are new to science. Interestingly, many of the better-known calcareous species in these samples also occur in the Northern Hemisphere. For example, *Epistominella arctica,* which is fairly common on the Weddell Abyssal Plain, was first described from the Arctic Ocean. No obvious morphological differences have yet been found between specimens of *E. arctica* from the polar regions. The metazoan meiofauna of the Southern Ocean deep sea was little known below generic level. However, the few studies undertaken have revealed a high diversity with as many as forty genera present in individual samples. A similar situation has been observed for harpacticoid copepods, and several new species are currently being described. Data on the entire metazoan size fraction (32–1000 μm) from the South Sandwich Trench revealed unexpectedly high standing stocks, predominantly of nematodes. These were higher values than known for deep-sea areas of the other world oceans. In particular, the deepest trench sample (6300-m water depth) yielded unusually high meiofaunal abundances, despite apparently low food availability. It might be that turbidites are responsible for these findings in a very steep trough, which might serve as some sort of a "sink" for the animals.

Data on the macrofauna from the Southern Ocean deep sea have shown that, in very general terms, this faunal component is similar in composition at a higher taxonomic level to that of other deep-sea regions of the world oceans. Nevertheless, most of the macrofaunal species are new to science, and many of these are so rare that it will be difficult to describe them all. For example, Southern Ocean deep-sea Isopoda show a high degree of endemism, being almost as high as on the shelf (85%), probably due to the negligible sampling effort in the Southern Ocean deep sea in the past. From 317 species of Isopoda sampled during the recent Southern Ocean deep-sea expeditions (ANDEEP), 141 were only found at a single station, and sometimes represented by few specimens or even just one. Similarly, a further 79 species were only found at two stations and only 91 (of 317) at more than two stations. Interestingly, the percentage of Amphipoda was much higher than known for other deep-sea areas. By contrast, within the Polychaeta many more species seem to have crossed the barrier between the Southern Ocean and adjacent oceans, possibly due to the differences in biology. As far as we know, brooding is much less common among polychaetes, and larval dispersal might be a reason for the wide distributions observed. Data on reproductive stages of some species suggest that these are limited to abyssal depths and are also reproducing there, while other species with broader depth ranges may be receiving recruits from slope depths. The deep-water bivalve fauna of the Southern Ocean is poorly known; however, the fauna sampled during ANDEEP was species-rich, indicating a lack of decline in diversity with depth in Antarctic bivalves. Current bivalve species richness in Southern Ocean deep water is probably a major underestimate due to the paucity of sampling.

Underwater photography has demonstrated megafauna to be less diverse in the Southern Ocean deep sea, especially below 2300 m. Evidence to date suggests the most abundant taxa are Porifera, Mollusca, Echinodermata, and Brachiopoda. However, within all taxa new species are being discovered. There seem to be gradients in species composition within the Weddell Sea from west to east, with a higher species richness in the western Weddell Sea, as has been found in some of the macrofauna (e.g., the Peracarida).

Many more expeditions and sampling in remote and inaccessible areas will be necessary to improve our knowledge and understanding of Southern Ocean biodiversity and its functioning. The IPY (International Polar Year 2007–2008) offers a unique chance to fill in the gaps.

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See also **ANDEEP Programme; Antarctic Bottom Water; Benthic Communities in the Southern Ocean; Circumpolar Current, Antarctic; Circumpolar Deep Water; Deep Sea; Echinoderms; Fish: Overview;**

Geological Evolution and Structure of Antarctica; Gondwana; Ice Ages; Larvae; Marine Biology: History and Evolution; Molluscs; Nematodes; Plate Tectonics; Polar Front

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BIODIVERSITY, TERRESTRIAL

According to the Convention on Biological Diversity, biological diversity (or biodiversity) means the variability among living organisms from all sources, including *inter alia,* terrestrial, marine, and other aquatic ecosystems, and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems. There are a variety of other definitions of biodiversity, but this one has considerable importance because many countries have signed and ratified the Convention on Biological Diversity, which has as its objectives "The conservation of biological diversity, the sustainable use of its components, and the fair and equitable sharing of the benefits arising from the utilization of genetic resources."

Although biodiversity includes all levels in the genealogical (genes to higher taxa) and ecological (individuals to ecosystems) hierarchies, there are significant relationships between various components of biodiversity. For example, strong relationships exist between numbers of species (richness) and numbers of higher taxa such as genera, families, and orders, between numbers of species and numbers of characters (or morphological features), and between numbers of species and the diversity of functional roles in an ecosystem that any one assemblage might have. Much present knowledge of biodiversity concerns patterns in species-richness variation across space and through time. Therefore, the relationships between species richness and other components of biodiversity mean that at least the fundamental patterns of this variation, if not the mechanisms underlying it, are reasonably well understood.

Spatial patterns in biodiversity are complex and three-dimensional. Species richness in marine, terrestrial, and freshwater systems varies with both latitude and longitude. Arguably the best-known pattern in species-richness variation is the latitudinal gradient in diversity, which encompasses a decline in richness from the tropics to the poles. It was first documented by Alexander von Humboldt (in 1804), and has been the subject of intense debate ever since. In marine and freshwater lake systems richness also varies with depth, whilst in terrestrial and freshwater stream systems, richness also changes with altitude. In virtually all cases, the gradients are neither linear nor symmetric, but show substantial variation depending on the region, the system (marine, freshwater, terrestrial), and the organisms of interest.

Ultimately, the species richness of an area depends on four main processes: speciation, extinction, immigration, and emigration. The relative importance of these processes depends on both the spatial and temporal scale of interest. More proximate determinants of richness variation include available energy (e.g., coming in as infrared, visible, and UV radiation, and often measured as temperature or net primary productivity), area (larger areas have more species for a variety of reasons), evolutionary rates (faster life cycles and high-energy environments lead to more speciation), and the effects of history of an area, which might substantially influence present diversity. The proximate determinants also include a null model, which posits that because of the constraints of a bounded domain, richness must be highest in its centre, so accounting for tropical peaks in richness.

From a terrestrial and freshwater perspective, the low-energy environment and isolation of Antarctica mean that it is species poor. Indeed, terrestrial and freshwater systems of Antarctica represent the end-point of the global cline in diversity. Where life can exist, richness is typically low, and continental Antarctic systems represent some of the simplest in the world. For example, some endolithic communities are restricted to a few species of algae, fungi, and bacteria. In Ellsworth Land (75°–77° S) the simplest faunal system comprises five tardigrade and two rotifer species. Even the nematode worms, which are known from harsh, poor environments such as the Dry Valleys, are absent here. In lakes the systems are dominated by phytoplankton and the microbial loop, with few invertebrates and no fish. Nonetheless, gradients in diversity exist on the continent in terrestrial and freshwater systems and are especially pronounced along the Antarctic Peninsula. The sharp distinction between the biotas of the peninsula and the continental Antarctic is also an important terrestrial biogeographic feature, with the peninsula biota typically representing more recent colonists and that of the continental sites including several Gondwana relics. Richness variation in continental Antarctica is spatially complex, reflecting regional and local variation in conditions as much as it does the increasingly low energy and isolated environment towards the pole. This variation is poorly understood owing to limited sampling in many areas, especially of the East Antarctic. Nonetheless, it is apparent that in many groups the species are wholly endemic (i.e., restricted to the region) to Antarctica (nematode worms) or nearly so.

Although the terrestrial and freshwater environments are species poor, the species often occupy environments that are otherwise not utilized elsewhere, show a range of remarkable strategies for overcoming Antarctic environmental challenges, and inhabit ecosystems which are often dominated by groups which are less noticeable elsewhere on the planet. For example, molecular techniques are now starting to reveal that the diversity of microbes in the Antarctic is complex and rich. Just how diverse it is by comparison with other systems is difficult to ascertain given that the techniques used for studying such diversity are novel. However, it seems likely that the microbes of Antarctica will prove to be extraordinary from a variety of perspectives. In the case of another group, the algae, the diversity of lifestyles is remarkable, including species which live within rocks with no obvious connection to the outside, as well as those that occupy small, seasonally liquid depressions on the surface of glaciers. In lakes, many protozoan species are mixotrophic such that they can alternate between particulate feeding and photosynthesis. In the most southerly lakes, these species are dominant and feed on bacteria during the winter and produce energy by photosynthesis during the summer.

Terrestrial and freshwater diversity increases rapidly from the maritime Antarctic to the sub-Antarctic islands. On the latter, variation in richness is comparatively well understood, especially in the case of vascular plants and insects, and to some extent in the bryophytes. Although the ways in which species have come to be present on the islands has been a controversial topic, there is increasing evidence for the importance of dispersal by wind, especially for the bryophytes and for some of the insects. Vicariance (or the presence of the species on a landmass as a consequence of its connection once to another landmass) is also though to be important for some groups. Richness variation of the indigenous vascular plants and insects is a consequence of energy availability, island area, and to a lesser extent isolation. The differential effects of glaciation, once though to be important for this variation, are less significant than variation in available energy. Thus, the largest and most northerly islands generally have the highest plant and insect species richness.

In marine systems the picture is much more complex. The biogeography of the region is influenced by the oceanic fronts, such that pelagic plankton can be divided into Antarctic, sub-Antarctic, and sub-Tropical assemblages. However, species-richness gradients are not straightforward. In some groups, such as the decapod and stomatopod crustaceans and bivalves, richness is low, and brachyuran crabs (i.e., typical crabs) are entirely absent from the region. However, in others there seems to be almost no decline in Antarctic waters (or a converse pattern). Thus, the pycnogonids (sea spiders), echinoderms (sea urchins and their relatives), and polychaetes (segmented worms) are especially rich in the Antarctic region. Indeed, in the case of the sea spiders the Antarctic region may be the area of highest richness globally. Other groups, such as the notothenioid fish, have also diversified dramatically in the Antarctic. Although the Antarctic fish fauna is notably species poor, this is not true of the notothenioids. Of the 174 benthic or demersal fish species known from the Southern Ocean, 55% are notothenioids, and these fish commonly represent more than 90% of the individuals collected. The group has undergone a remarkable adaptive radiation in shallow water around Antarctica and dispersal through the Polar Front has resulted in divergence of other sub-Antarctic notothenioid species. These fish are endemic to the Antarctic region, although recently a Patagonian toothfish was discovered off Greenland, lending support to the idea that transequatorial dispersal events can take place in deep, cold water.

Although the distribution of benthic and pelagic diversity across the Southern Ocean is poorly understood for most groups owing to the paucity of information, especially for the East Antarctic, one group is especially well known. The seabirds, which are essentially pelagic species that return to land to breed, have been well documented both in terms of their breeding populations and their at-sea distributions. Species richness peaks in the vicinity of the Polar Front, and globally the proximate determinants of this richness are primary productivity, sea-surface temperature, wind speed, and to a lesser extent the accessibility of breeding sites. The majority of these variables reflect the overwhelming importance of energy availability in determining richness of this pelagic group of animals.

In terms of functioning, terrestrial ecosystems are influenced predominantly by temperature and water availability, though nutrient availability is also important. Both human (cloche-type enclosures) and natural (heated-ground) experiments have demonstrated the influence of temperature and water availability on the identity and abundance of species in Antarctic habitats. Terrestrial systems are dominated by particulate feeding and detritivorous heterotrophs, and one or two species are most abundant at a given site. Predation is not uncommon, but it is rarer than elsewhere, and parasitism is infrequent. Functional roles typical of warmer climates, such as pollination, are poorly represented in the Antarctic. In freshwater ecosystems, food webs tend to be simple, and connections may span several levels. Marine systems in the Southern Ocean are complex and incorporate a wide range of ecological processes, ranging from disturbance such as ice scour in shallow-water environments to considerable trophic complexity associated with pelagic top predators such as whales, seals, and penguins. The sea-ice environment plays an especially important role in ecosystem dynamics in the Southern Ocean, and recent changes to sea ice are having far-reaching biodiversity consequences. Genomic studies are proving instrumental in unravelling survival strategies and ecological interactions in marine and terrestrial systems.

Antarctica was not always glaciated. Indeed, the first continental ice sheets appeared in Antarctica about 34 Ma. In consequence, the fact that Antarctica supported a diverse terrestrial biota, including plants, insects, and even dinosaurs is not surprising. However, the extent of this fossil biota is only beginning to be explored, and remains poorly known for many groups. For example, the first Cretaceous fossil that can definitely be placed within the modern bird radiation hails from Antarctica. From about 10 Ma, Antarctic ice sheets were substantial and well established, and would have extirpated the bulk of the terrestrial and freshwater biotas, though some terrestrial relict species remain. Orbital forcing is thought to have driven expansion and contraction of the Antarctic ice sheet, so periodically covering and exposing continental shelf habitat in the sea surrounding Antarctica. These changes are likely to have subdivided populations and caused substantial changes to their ranges, promoting speciation. This mechanism is thought to be one of the causes of high diversity in several Antarctic marine groups.

Subsequent to the development of the Antarctic Circumpolar Current, the continent has remained relatively isolated. However, this isolation is not complete and organisms have migrated both into and out of the region. Aeolian (wind) transport of propagules (cysts, eggs, larvae, seeds, spores, plant parts) from South America to the Peninsula region are not uncommon, especially under stormy weather conditions, and kelp rafts (and more recently floating plastic debris) may form another source of transport of colonists across the Southern Ocean. In addition, a wide range of pelagic mammal and seabird species regularly migrate into and out of the region, so overcoming the isolation barrier. However, even for those propagules that can cross the barriers which separate Antarctica from the other continents, the low temperature and low productivity environment (in the winter in marine systems) represent a significant challenge to establishment and survival.

More recently, the routes for colonization have increased substantially thanks to human traffic to Antarctica, first by ship and now by aircraft too. Thus, humans have introduced a wide range of alien, and in many cases invasive, species to Antarctica and the sub-Antarctic islands. These include microbes (and the diseases they cause in some cases), algae, fungi, bryophytes, vascular plants, invertebrates, fish, birds, and mammals. These species have come to survive, and in some cases dominate, terrestrial, freshwater, and marine habitats, in some regions causing considerable damage by way of species extirpations and wholesale alteration of ecosystems. On the sub-Antarctic islands the effects of invasive species are well known. For example, rats and cats have caused the disappearance of seabird species from several islands, whilst eradication of the alien species has seen the return of the birds. Alien plants reduce local diversity by as much as 40%, and invasive rodents have caused wholesale alterations to ecosystem functioning. The indirect effects of species such as insects, mice, reindeer, and salmonid fish are only beginning to be appreciated. Alien species arrive in a multitude of ways: in clothing and personal baggage, attached to fresh vegetables, in vehicles, affixed to the hulls of ships and inflatable rubber boats, and as unwanted passengers on anchor chains, in sea chests, and in ballast water.

Across the Southern Ocean islands there is a strong relationship between the numbers of humans that visit an island and the numbers of species that have successfully been introduced to an island. This relationship between visitor frequency and numbers of alien and invasive species has been established elsewhere and seems to be a general rule. Moreover, there is also a strong relationship between energy availability and numbers of alien species on the Southern Ocean Islands, suggesting not only that warmer islands are more at risk, but also that climatic amelioration is likely to enhance the risks of invasion.

Recent increases in human activity in the Antarctic have been considerable. For example, in the 2001–2002 season, Treaty nations deployed 4390 personnel at 67 stations or field camps in Antarctica. They also made use of some sixty ships, departing from about thirty cities around the world, to offload personnel and cargo. Tourist numbers doubled from approximately 6000 in 1992 to about 13,600 10 years later, most of whom visited the Peninsula region. From 1996 to 2006, the numbers of ships and passengers visiting South Georgia have increased threefold to fourfold. In 2001–2002, nearly 7000 people visited a single site: Whalers Bay, Deception Island.

Moreover, in the Peninsula Region, and at many sub-Antarctic sites, climates have warmed dramatically over the past 50 years, making these environments more benign than they once were. Thus, both the isolation and the climatic barriers that long meant low colonization rates of Antarctica are being influenced by human activities. In consequence, the chances of successful colonization of the Antarctic by alien species are likely to increase substantially unless appropriate mitigation measures are put in place. In this instance, prevention is more economically viable than eradication programmes, which are usually expensive and often long-term.

Although the Convention on Biological Diversity calls for the conservation of biodiversity via a variety of measures, including the prevention of invasion and/or eradication of alien species, it does not apply to the Antarctic Treaty area. However, it does apply to the sub-Antarctic islands that have been annexed by those nations which have ratified the Convention. Many sub-Antarctic islands are managed as IUCN Category 1 Nature Reserves. Nonetheless, the conservation regulations at the islands vary widely, from extremely strict (e.g., no tourism, no fresh produce ashore at the Prince Edward Islands) to much less demanding (e.g., Îles Kerguelen and South Georgia). A formal, spatially explicit conservation assessment of the Southern Ocean islands has shown that by strictly conserving 15 of the Southern Ocean Islands, 90% of species richness can be captured, whilst only 50% of the alien species are included. Unfortunately, the generally strong relationship between alien and indigenous species richness means that some level of the latter will always be included. Moreover, planning for the biodiversity effects of climate change is made difficult both by the high levels of endemism in the region and by the likelihood that climate change will favour alien over indigenous species. Nonetheless, the formal analysis demonstrated that using spatially explicit data and modern analytical methods provides a more robust approach than expert consultation, which in this particular case rarely proved better than simply picking islands at random.

In the Treaty Area, the conservation of biodiversity is undertaken by the Antarctic Treaty Consultative Parties under the auspices of the Committee for Environmental Protection, established under the Protocol on Environmental Protection to the Antarctic Treaty. Conservation is also facilitated by other organs of the Treaty system, such as the Convention for the Conservation of Antarctic Seals and the Convention for the Conservation of Antarctic Marine Living Resources. Whilst there are a wide range of measures in place for the conservation and sustainable use of biodiversity in the region, rational, spatially explicit conservation planning, which has been undertaken for many other parts of the globe, lags far behind in the Antarctic. In some cases, such as for marine benthic and pelagic diversity, this is a consequence of data deficiency, and only a sustained survey effort is likely to alter the situation. However, there are spatially explicit data for some groups, such as the seabirds and increasingly the seals, and much local-scale data on terrestrial biodiversity is available as a consequence of the requirements for the establishment of Antarctic Specially Protected Areas (ASPAs) and Antarctic Specially Managed Areas (ASMAs). However, these data have yet to be used to develop a formal, spatially explicit conservation planning framework for Antarctica. If the biodiversity of the region is to be conserved and used in a sustainable manner, then such a framework, which incorporates the likely substantial changes that will be wrought to marine, freshwater, and terrestrial systems by climate change and the patterns of human use of the region, is urgently required.

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See also **Aerobiology; Algae; Antarctic Peninsula; Antarctic Treaty System; Benthic Communities in the Southern Ocean; Biodiversity, Marine; Biogeography; Circumpolar Current, Antarctic; Climate Change; Climate Change Biology; Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Convention on the Conservation of Antarctic Seals (CCAS); Cryoconite Communities; Deception Island; Dry Valleys, Biology of; Echinoderms; Fish: Overview; Food Web, Freshwater; Fungi; Gondwana; Heated Ground; Insects; Kerguelen Islands (Îles Kerguelen); Microbiology; Nematodes; Pelagic Communities of the Southern Ocean; Phytoplankton; Polar Front; Prince Edward Islands; Protected Areas within the Antarctic Treaty Area; Protocol on Environmental Protection to the Antarctic Treaty; Protozoa; Rotifers; Seabirds at Sea; South Georgia; Springtails; Streams and Lakes; Tardigrades; Toothfish; Tourism; Wind**

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BIOGEOCHEMISTRY, TERRESTRIAL

Biogeochemistry is the study of cycling of the biologically essential elements, principally: carbon, hydrogen, oxygen, nitrogen, phosphorus, and sulfur. In terrestrial Antarctica, biogeochemical cycling is controlled by the extreme climate, limited biodiversity, and biological activity, and by ecological "legacies" that influence the spatial distribution and availability of resources necessary to support life: water, organic matter, and inorganic nutrients. An ecological legacy is a carry-over effect or influence of past climates, geological events, or previous biological activity that is imprinted on the contemporary ecosystem. Examples of legacies that affect terrestrial ecosystems include paleolake sediments, glacial tills, and avian colonies. The consideration of legacies is vital to understanding the biogeochemistry of terrestrial Antarctic soils and neighboring ecosystems such as streams, lakes, and glaciers.

Carbon is the most fundamental of the biogeochemical cycles. Extreme climate limits photosynthesis (carbon fixation) by plants, lichens, and algae and by chemautotrophic bacteria, and as a result, Antarctic soils have among the lowest organic carbon concentrations found in terrestrial ecosystems. Sources of organic carbon include lake sediments, algal mats, and mosses in saturated soils adjacent to streams and lakes, avian rookeries, rock-dwelling lichens, and endolithic microbial communities, and higher plant communities on the Antarctic Peninsula. The chemical and isotopic signatures of carbon and nitrogen in the McMurdo Dry Valley soils indicate that the deposition of carbon-rich paleolake sediments formed under previous climates accounts for much of the organic matter supporting current biogeochemical activity. Rates of carbon cycling, measured as carbon dioxide (CO_2) flux from soils, are among the lowest reported anywhere in the world.

While carbon is limiting to terrestrial food webs in many Antarctic ecosystems, other elements such as nitrogen and phosphorus are often in high supply, resulting in elemental ratios that differ from the theoretical proportions necessary for biological metabolism and balanced growth. Controls over the accumulation and biogeochemical cycling of nitrogen, phosphorus, and trace element constituents of salts and marine aerosols (e.g., sulfur, potassium, calcium, and sodium) are influenced by the proximity of marine sources, soil age, the amount of mineral weathering, and the ecological legacies of the landscape. High-elevation, ice-free regions in continental Antarctica are some of the oldest continually exposed surfaces on the planet with high salt concentrations from the long depositional history and negligible rates of soil leaching. Nitrate (NO_3), usually found in very low amounts in productive ecosystems, can reach concentrations as high as 3% of soil weight, resulting from low rates of atmospheric deposition over millennia and very low rates of biological cycling.

Antarctic terrestrial ecosystems maintain small amounts of organic matter, with very slow rates of biogeochemical cycling that may be sensitive to subtle shifts in climate. Biogeochemical cycling in Antarctic ecosystems is highly dependent on ecological legacies, is limited by the low biotic potential of the environment, and is constrained by the availability of liquid water. Small variations in climate from natural or anthropogenic change influence the availability of liquid water and may significantly alter the balance between physical and biological controls over the biogeochemistry of this sensitive landscape.

J. E. Barrett and Ross A. Virginia

See also **Algal Mats; Antarctic Peninsula; Biodiversity, Terrestrial; Carbon Cycle; Cryptoendolithic Communities; Dry Valleys; Lichens; Mosses; Penguins: Overview; Soils**

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BIOGEOGRAPHY

Biogeography is the study of biological distributions at geographical scales. At a very simple level, biogeographical data allow us to know "what occurs where," thereby quickly becoming linked with studies of biodiversity. Descriptions of biogeography are fundamental to any attempt to understand the wider evolutionary relationships of and between the biota and biology of different regions of the Earth. Biogeographical patterns can also provide considerable insight to nonbiological disciplines, such as in the reconstruction of geological (tectonic) relationships, or of glacial history.

Biogeography clearly has a fundamental reliance on the quality of taxonomic knowledge available or, in other words, the ability to identify distinct taxonomic units. Until recent years, taxonomy was based on traditional morphological approaches to the description of species. With the advent of molecular biological approaches, and in particular the use of complex and demanding computing resources to allow the construction of molecular phylogenies, a second and parallel approach has become available to researchers. However, while the two approaches often produce similar results, this is not always the case, leading to areas of contention that are still to be resolved. Molecular phylogenetic approaches have the potential to identify speciation events in situations where morphological differentiation through traditional approaches is not possible (e.g., "cryptic speciation"), and also in the earlier stages of differentiation that must occur within a species and that underlie later speciation. Again, this has led to further and largely unresolved philosophical debate over how to define a species—not least as most classical and molecular phylogenetic studies are not linked to autecological knowledge of the living taxa concerned, while the level of differentiation (if any) required for taxonomic definition, and whether this can be generalised across species and higher taxa, is also far from clear. Molecular approaches are also starting to be applied to groups of microbiota, the dominant biota across much of Antarctica, where classical approaches are largely redundant and existing data very inadequate. Finally, the potential of "molecular clock genes" (highly conserved genes with predictable sequence-mutation rates) is starting to be applied in Antarctic studies, although here it is important to note that it is often not possible with the very limited fossil record, particularly for invertebrate and microbial groups, to provide an independent constraint on the dating of separation events.

The terrestrial biota of the Antarctic exists in a clearly defined element of the globe, more isolated (by physical scale and environmental extremes) from external contact than any other continental landmass. The study of the biogeography of Antarctic terrestrial biota provides clear potential for the identification of ancient evolutionary linkages with other Southern Hemisphere continents and of intraregional evolutionary processes, including signals of geological and glaciological history, as well as for the understanding of regional and global colonisation processes.

In Antarctica 99.5% of the continental area is covered permanently by snow or ice. Ice-free ecosystems include nunataks, cliffs, and areas exposed seasonally to snow and ice cover. Terrestrial habitats are more extensive, and their exposure is of longer duration, on the oceanic sub-Antarctic islands surrounding the continent. On the continent and Antarctic Peninsula, most ice-free areas are inevitably small in extent and isolated from their nearest neighbours by distances of tens to hundreds of kilometers. Antarctica as an entity is isolated from the other southern continents by the Drake Passage south of Tierra del Fuego (1000 km), and by 4000–5000 km from Australia and South Africa.

In the context of geological history and evolution, Antarctica was a section of the Gondwanan supercontinent. As Gondwana broke up, Antarctica's last continental links were with Australia and South America. The final loss of the Antarctic Peninsula–South America link, through the formation of the Drake Passage, took place 50–30 Ma. This event was fundamental in the climatic evolution of Antarctica, as it allowed the development of circum-Antarctic oceanic and atmospheric circulation patterns that effectively cut the continent off from lower latitudes, allowing continental cooling to commence. However, even though lying at high southern latitude throughout this period, Antarctica was not initially glaciated and fossil evidence clearly indicates a cool temperate fauna and flora closely similar to those then present in South America and Australia/

Dominant Biotic Components of Typical Ecosystems of the Three Antarctic Biogeographical Zones

Zone	Flora	Fauna	Microbiota
Sub	Low altitude/coastal: flowering plants (phanerogams), ferns, bryophytes, lichens (cryptogams); higher altitude/inland: open fellfield (similar to maritime zone); nonindigenous introductions	Arthropods (largely Insecta); micro-arthropods (Acari, Collembola); micro-invertebrates (Nematoda, Tardigrada, Rotifera); alien vertebrates and invertebrates	Various groups, poorly documented in detail
Maritime	Two flowering plants, limited distribution; closed and open fellfield cryptogam communities	Diptera very limited; micro-arthropods (Acari, Collembola); micro-invertebrates (Nematoda, Tardigrada, Rotifera)	Algal and cyanobacterial mats; foliose algae; protozoa
Continental	Bryophytes and lichens, more limited extent than in maritime zone	Micro-invertebrates; micro-arthropods (Acari, Collembola) more limited	Algal and cyanobacterial mats; protozoa; endolithic fungi, algae, cyanobacteria

Modified from Convey 2001.

New Zealand. Even after the commencement of glaciation, ice extent and distribution has varied widely over time, with evidence of warmer periods as recently as 8–10 million years ago that were again sufficient for the development of areas of cool temperate *Nothofagus* forest.

When the sub-Antarctic is included, Antarctic terrestrial environments can be characterised as including all exposed ground south of approximately 50° latitude. Not unsurprisingly in such a large area, a wide range of terrestrial ecosystems is present and several systems of classification have been proposed. In recent years, most commonly three biogeographical zones are recognized, the sub-Antarctic, maritime Antarctic, and continental (or frigid) Antarctic. The terrestrial ecosystems and climatic characteristics of the three zones are distinctively different.

The sub-Antarctic zone includes a series of isolated islands and groups lying at high latitudes in the Southern Ocean. Apart from South Georgia, Heard Island, and the McDonald Islands, these are located close to or north of the oceanic Polar Frontal Zone. The term "sub-Antarctic" has also been used in a wider sense in some publications to include some more northern island groups that are better described as "oceanic cold temperate," including the Falkland Islands, Gough Island, Île Amsterdam, and the New Zealand shelf islands. Sub-Antarctic island climates are strongly influenced by the surrounding ocean, which restricts temperature variation (mean monthly temperatures are positive for 6–12 months of the year), while the islands are generally not influenced by seasonal pack or fast ice.

The maritime Antarctic includes the western coast of the Antarctic Peninsula as far south as southern Alexander Island (around 72° S), the archipelagoes of the South Shetland, the South Orkney and South Sandwich Islands, and the isolated islands of Bouvetøya and Peter I Øy. It is important to note that the Antarctic Peninsula element, which includes neither the central mountainous spine and the eastern coastal regions nor the basal portion of the peninsula including Ellsworth Land, does not equate to the geological region of West Antarctica. Like the sub-Antarctic, the maritime region also experiences an oceanic influence on its climate, especially during the austral summer period after the loss of any winter sea ice. The South Sandwich Islands and Bouvetøya are exceptional, as they are geologically young (1- to 3-million-year-old) volcanic islands that continue to experience geothermal activity, and they possess unique biological communities associated with heated ground. Air temperatures in the maritime Antarctic are positive (but <2°C) for 1–4 months of the year, while winter mean temperatures are also buffered by the surrounding ocean, and short thaws may occur throughout the winter.

The final zone, the continental Antarctic, is by far the largest in areal extent and includes all of East (or Greater) Antarctica, the Balleny Islands, and the eastern side of the Antarctic Peninsula. Terrestrial habitats here are typically of limited extent and great isolation, and include areas of coastal exposure comparable with those of much of the maritime zone, and inland nunataks and mountain ranges. One particular exception to this generalisation is the extensive (about 4000 km^2) ice-free cold desert region of the Victoria Land Dry Valleys. Temperature regimes experienced even in coastal areas of the continental zone are more extreme, with positive mean air temperatures achieved for <1 month of the year. Inland, positive air temperatures may never be seen, while winter minima drop regularly to –60°C or below. Microhabitat temperatures (i.e., where the biota actually live) do not necessarily track air temperatures, and continental habitats with no winter snow protection are likely to be exposed directly to winter air temperature extremes. Conversely, during the short summer, even at the most southern locations with exposed ground or rock (nunataks and mountain ranges at 84–87° S), absorption of solar energy by rock and soil substrata is sufficient to lead to melting and the release of liquid water to temporary streams, pools, and lakes.

Climatic and environmental factors are important determinants of the biota that can exist in any given location. In the Antarctic, seasonal snow and ice cover, which provides a buffer to extreme low temperatures, rapid temperature fluctuation, and wind/ice abrasion, is one such factor. This affects all three zones, but is particularly significant in the maritime and continental Antarctic, where habitats may become free of snow for as little as a few weeks to months, and occasionally not at all in the continental zone. In contrast, most sub-Antarctic islands experience only intermittent snow cover. At the lower altitudes near the coast, microhabitat temperatures often remain positive or only just below the freezing point, and this is sufficient to allow continuous invertebrate activity.

Soils are another component of the environment with a potentially significant influence on levels of biodiversity achieved and on distributional limits. Most Antarctic soils are poorly developed, with low organic content. Brown soils are present only where more extensive communities of higher (flowering) plants have become established, and are thus better represented in the sub-Antarctic, with very limited occurrence in the maritime and none in the continental zones. Moss peat deposits are distributed in a similar pattern, while also a source of strong evidence

Estimates of Biodiversity of Native Terrestrial Invertebrate and Plant Taxa in the Three Antarctic Biogeographical Zones

Group	Sub-Antarctic	Maritime Antarctic	Continental Antarctic
Protozoa*	83	83	33
Rotifera*	ND	ND	13
Tardigrada	>29	26	20
Nematoda*	22	40	10
Annelida (Oligochaeta)	23	3	0
Mollusca	5	0	0
Crustacea (terrestrial)	6	0	0
Crustacea (nonmarine but including meromictic lakes)	48	11	11
Insecta			
Collembola	>100	10	10
Mallophaga	61	25	34
Diptera	44	2	0
Coleoptera	40	0	0
Arachnida			
Araneida	20	0	0
Acarina	140	36	29
Myriapoda	3	0	0
Flowering plants	60	2	0
Ferns and clubmosses	16	0	0
Mosses	250	100	25
Liverworts	85	25	1
Lichens	250	250	150
Macrofungi*	70	30	0

Modified from Convey 2001.
ND, number of representatives of group unknown.
*Large changes likely with future research due to current lack of sampling coverage, expertise, and/or synonymy.

(through radiocarbon dating) that extensive plant colonisation only occurred in the sub-Antarctic and maritime Antarctic in concert with post-Pleistocene glacial retreat. A further important factor in consideration of soil properties is the existence of widespread permafrost in the maritime and continental zones and more limited permafrost in the sub-Antarctic. This, in combination with periglacial cryoturbation processes, means that Antarctic soils are particularly unstable and mobile, affecting their availability to biota during the processes of colonisation and establishment.

Of the groups of biota represented in Antarctica, terrestrial vertebrates form an exceptionally small component in comparison with any other continental region, and the few that are found are limited to the sub-Antarctic. These are all birds (one passerine and two ducks; two scavenging sheathbills are also associated with the presence of marine mammals and birds), and there are no indigenous land mammals, reptiles, or amphibians. The sub-Antarctic in particular, but also coastal regions of the maritime and continental zones and even multiyear coastal fast ice, are home to globally significant populations of seabirds and mammals, and these can have a considerable impact on their local terrestrial habitats through manuring, aerosol transport of nutrients, and direct trampling.

At a large geographical scale and coincident with the environmental gradient of increasing severity between the sub-Antarctic and continental Antarctic, there are generally recognised gradients of decreasing biodiversity and community complexity, as well as progressive loss of evolutionarily more advanced groups. A range of "higher" arthropod groups is found in the sub-Antarctic, although even here diversity at higher taxonomic levels remains very limited—for instance, the majority of insects are drawn from Diptera (flies) and Coleoptera (beetles). Although detailed inventories for some taxonomic groups have been prepared at some sub-Antarctic islands, and it is known that diverse micro-arthropod (Acari, Collembola) and micro-invertebrate (Nematoda, Tardigrada, Rotifera) communities are present, surprisingly little research effort has been devoted to these groups across the entire zone, and little concrete information can be concluded about their biogeography.

Similarly, the sub-Antarctic flora is the richest of the three zones. Both phanerogams (flowering plants) and cryptogams (ferns, mosses, liverworts) are found, although, with a single exception on Macquarie Island, woody trees and shrubs are absent. The indigenous species have strong affinities with either southern South America or Australia/New Zealand. These floras appear to be very vulnerable to the impacts of invading or introduced nonindigenous species, most of which result from human activity. This may take the form of either grazing pressure from introduced mammals and invertebrates or direct competition and displacement by introduced weeds, and can result in the complete loss, currently at a local scale, of native plant (and, presumably, associated invertebrate) communities. On some sub-Antarctic islands the environmental conditions, including the lack of native grazers, have encouraged the development of a vegetation dominated by megaherbs (large rosette-forming plants) and tall tussock grasses.

Maritime Antarctic faunas are considerably less diverse than those of the sub-Antarctic, at both species and higher taxonomic levels. Higher insects are reduced to two chironomid midges (Diptera). The most common arthropods are mites (Acari) and springtails (Collembola). Micro-invertebrate groups are again well represented, although, as is typical of many Antarctic terrestrial biota, research coverage is very patchy and generally limited to specific sites visited by a small number of specialists. Faunal communities are species-poor—for instance, it is rare for more than about twenty species of arthropod to be known from any location, of which only a handful will be encountered in a cursory survey—but abundance or population density can be comparable to or greater than that seen in temperate ecosystems. Community trophic structure is very simple. The majority of invertebrates are thought to be microbivores and/or detritivores (although few specific feeding studies have been attempted), and predation is rare. For instance, the largest terrestrial predators in the maritime Antarctic are species of prostigmatid and mesostigmatid mite, of which at most two are present at any given location, and even these are often not obtained in many collected samples. True herbivory is unusual, possibly as a result of energetic constraints, although it is also generally the case worldwide that bryophytes and lichens (the dominant maritime Antarctic vegetation) are not selected by herbivores.

Vegetation over much of the maritime Antarctic is often described as "fellfield," with scree, boulder fields, and simple soils colonised by a range of cryptogamic vegetation (mosses, liverworts, lichens). In particularly favourable locations closed cryptogam communities are present, in some cases allowing the formation of layers of moss peat. Two higher plants, the hairgrass *Deschampsia antarctica* and the pearlwort *Colobanthus quitensis,* are also often present in these richer sites, and they are the only higher plants found on the Antarctic continent. As with the majority of the bryophytes, these two plants have South American distributions extending well outside the confines of Antarctica, in this case northwards along the Andean mountain chain. Cryptogamic vegetation is sensitive to physical disturbance, which, in the maritime Antarctic, takes the form of trampling from penguins and seals near their breeding colonies or resting sites. Here, vegetation is often either nonexistent or dominated by the foliose alga *Prasiola crispa*.

In terms of the groups represented, the terrestrial fauna of the continental Antarctic is similar to that of the maritime zone, except that the higher insects are lost, and most micro-arthropods have much more restricted distribution. Throughout most continental Antarctic terrestrial habitats, soil meiofauna are dominant. These faunal communities are recognised as amongst the simplest on the planet, with some large areas even lacking the nematode worms, a group that is otherwise ubiquitous worldwide. Even these simple communities do include predatory species of nematode or tardigrade. Likewise, continental Antarctic vegetation is similar in composition to that of the maritime zone, except that no phanerogams are present, bryophytes are much more restricted in diversity and spatial extent, and lichens become dominant.

In comparison with the level of knowledge available for macrobiota, and allowing the previously mentioned caveat of biases towards a limited number of detailed sampling areas, as well as the work of the small number of specialists, the level of biogeographical or even simply biodiversity data available for most microbial groups is minimal. Microbial autotrophs are recognised as fundamental to polar terrestrial ecosystem processes, being the primary colonists and sometimes the only biota present. Microbes such as fungi, algae, and cyanobacteria also play a central role in the stabilization of mineral soils, a key prerequisite for secondary colonization and subsequent community development involving other microbiota and macrobiota.

Microbes are found in all of the habitats also occupied by macroscopic faunal and floral communities—in or associated with soils, rocks, and vegetation. Fungi, algae, and cyanobacteria are often visible as filaments or mats, often associated with water bodies or damp soils. Microbial communities are well represented in all three zones, becoming visually more obvious as macroscopic groups decline in the maritime zone and often forming the climax community in the continental zone. However, and unlike representatives of most other groups, microbial communities are also present in cryophilic habitats such as snow (a small number of metazoans, notably tardigrades and some protozoans, are also found in communities in small melt holes, cryoconites, in glacier surfaces). Endolithic microbial communities are also found within the surface layers of rock matrix, particularly associated with certain types of sandstone and relatively clear minerals such as gypsum. The latter habitats in the cold desert environments of the continental Antarctic may represent one limit to biological existence on Earth.

At first sight, there is an extensive literature pertaining to the general subject of Antarctic terrestrial diversity and biogeography. Current estimates for levels of diversity in the major groups of animals and plants represented in the three zones are summarised in the second table in this entry. However, in attempting to identify overall biogeographical patterns and compare between the three zones, two fundamental problems remain even for the visible macroscopic groups. First, sampling coverage is poor at best and completely inadequate at worst—for all groups, many locations remain to be visited, while for some groups current knowledge relies on data from a very few or even single sites, with virtually no targeted collections or visits by trained specialists. Second, taxonomic uncertainty (e.g., synonymy, undescribed species, unrecognised cryptic speciation) is present to some extent in all groups encountered.

These factors negate any possibility, at present, of rigorous biogeographical analyses' being applied to any microbial groups. Molecular biological approaches to the taxonomy of prokaryotic and eukaryotic microbiota give the promise of an imminent acceleration in the level of data available, although in both cases only a tiny fraction of diversity (global or Antarctic) has been described, or even simply recognised, to date. These molecular approaches are expected to allow the testing of a currently popular biogeographical hypothesis in Antarctica: the "global ubiquity hypothesis" essentially postulates that, since many microbial groups are extremely effective dispersers through their small size and possession of resistance adaptations, there should be more evidence of ubiquitous microbial distributions (or, at least, dispersal) than is the case for larger organisms. As yet, the evidence available is conflicting—on the one hand, based on classical approaches, it has been suggested that many Antarctic algae and fungi represent cosmopolitan taxa, whilst on the other, recent molecular analyses indicate considerable isolation and lack of exchange between different communities in similar habitats over very large geographical transects.

In contrast with the lack of microbial data, large-scale biogeographical patterns clearly exist in at least some macrobiota. Recent analyses of patterns across the islands of the Southern Ocean, including those of the sub-Antarctic and maritime Antarctic, have identified an overriding importance of wind dispersal in linking the biotas of different island groups and the southern continents, and a range of factors (including climate, area, vegetation type, human occupancy) as having explanatory value for the richness of specific groups within a given island or island group. However, other than demonstration of the frequency of occurrence of aerial dispersal events to a single maritime site, studies of this type have yet to be extended to the mainland of the Antarctic Peninsula (i.e., the remainder of the maritime Antarctic) or the continental Antarctic.

With reference to the maritime and continental zones, contemporary thinking is undergoing some rapid development. Since the studies of J. L. Gressitt and coworkers in the 1960s, it has been recognised that elements of the Antarctic terrestrial biota can (and most likely did) have two separate origins—an ancient and relictual element that has managed to survive through the extremes of glaciation, and a more recent colonist element, likely to have arrived in the Antarctic following the ice retreat from Pleistocene glacial maxima. However, most terrestrial biota in all three zones, but especially the sub-Antarctic and maritime Antarctic, are found in coastal, low-altitude areas. They seem unlikely to have survived glaciation in these sites (which would have been overrun by ice, at least in the maritime Antarctic and on the colder sub-Antarctic islands) or on higher-altitude nunataks, and their presence has been interpreted as evidence of post-glacial colonization from refugia on Southern Ocean islands or continentals. This is problematic because, as yet, no island or continental refugia can be identified with confidence. In continental Antarctica, some nunataks and other ice-free areas are proven to have survived Pleistocene glaciation, and analyses of their faunal communities is interpreted as showing evidence for a relict fauna predating the onset of Antarctic glaciation, and even giving indicators of the breakup of Gondwana itself.

The "recent dispersal" viewpoint is also inconsistent with evidence from patterns of endemism in some groups across Antarctica. Levels of endemism differ between the major taxonomic groupings represented, from the mosses where virtually all species present in Antarctica have wider non-Antarctic distributions, to the nematode worms, where possibly none are known outside Antarctica. For some groups, such as nematodes, mites, and springtails, there is also a clear and striking lack of overlap at species level between the different zones (particularly the maritime and continental Antarctic). Using lichens as an example, it is also the case that the Antarctic continent may provide a significant source of propagules dispersing northwards to lower latitudes—approximately 40% of the lichen flora of the geologically young and geographically isolated South Sandwich Islands are identified as species otherwise known only from more southern Antarctic locations. Most recently, molecular biological techniques have been used to illustrate the process of radiation and local colonisation from a regional centre in springtails from Victoria Land (continental Antarctica), and to propose the continuous existence of ancestral lines of endemic chironomid midges (Diptera) over tens of millions of years on the western Antarctic Peninsula (maritime Antarctic) and South Georgia (sub-Antarctic).

Finally, it is rapidly becoming clear that human activities pose perhaps currently the greatest single threat to the biogeographical integrity of Antarctica. First, as noted, humans already have a direct impact on regional biogeography through the import and release (historically, often deliberate, though today largely accidental) of nonindigenous species, with the sub-Antarctic being particularly vulnerable. As yet there are few research and monitoring programmes directed towards nonindigenous species in place. Available data indicate that the establishment of visible nonindigenous species of plant and animal (vertebrate and invertebrate) is reasonably well documented, but that the same cannot be claimed for any groups of microbiota. Second, human activity is expected to have a pervasive influence on regional biota through a crucial indirect route. Anthropogenic climate change is being experienced across the planet but, in some parts of the maritime and sub-Antarctic, this is occurring at the fastest rates recorded anywhere. In a purely Antarctic context, such change may simply relax the currently extreme environmental constraints acting on the physiology and ecology of native invertebrates and plants, and in these cases it can be interpreted as advantageous in the sense of accelerating growth and the life cycle. However, contemporary climate change is also expected to lower the barriers currently facing potential colonist organisms, thereby increasing the chance of survival of long-distance transport to the region, and the likelihood of successful establishment on arrival, with or without direct human assistance.

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See also **Adaptation and Evolution; Algae; Amsterdam Island (Île Amsterdam); Antarctic: Definitions and Boundaries; Antarctic Peninsula; Balleny Islands; Biodiversity, Terrestrial; Bouvetøya; Climate; Climate Change Biology; Colonization; Cryoconite Communities; Drake Passage, Opening of; Dry Valleys; Flowering Plants; Fungi; Gene Flow; Gondwana; Gough Island; Heard Island and McDonald Islands; Insects; Lichens; Liverworts; Microbiology; Mosses; Nematodes; Parasitic Insects: Mites and Ticks; Peter I Øy; Polar Desert; Polar Front; Protozoa; Rotifers; Soils; South Georgia; South Orkney Islands; South Sandwich Islands; South Shetland Islands; Springtails; Tardigrades; Temperature; Vegetation; Weddell Sea Region, Plate Tectonic Evolution of**

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BIOINDICATORS

Bioindication is the use of one or more species to identify, or demonstrate the impact of, a human-induced change in the abiotic or biotic environment. The species used to achieve this objective are bioindicators. Motivations for the use of bioindicators include the following: (1) species are sometimes more sensitive or informative indicators of environmental change than abiotic environmental measures; (2) in the absence of a comprehensive understanding of ecological processes and disturbance impacts, and insufficient resources to rapidly achieve such understanding, bioindicators are a practicable alternative; and (3) in the face of rapid environmental change, bioindicators are a comparatively efficient means of obtaining the information necessary for decision making. In Antarctica and the sub-Antarctic, human-induced environmental change takes the form of harvesting of marine resources; physical disturbance as a consequence of science, operational, and tourism activities; the impacts of alien species; pollution; and climate change. Thus, bioindicators have both realized and potential value to the understanding, conservation, and management of Antarctic ecosystems.

Three broad categories of bioindicator are distinguished based on clear differences in their objectives, namely environmental, ecological, and biodiversity indicators. Environmental bioindicators are used to demonstrate the existence or level of an abiotic environmental stressor, most typically a pollutant. For example, in the Antarctic, marine mollusks; plankton; kelp; lichens; bird and seal muscle, liver, and kidney tissue; and bird stomach contents, feathers, and eggs have all been shown to variously act as bioaccumulators (organisms that absorb compounds directly from the environment) of chemical, organic, and radionuclide contaminants. The presence of exploiter species (species whose presence is indicative of disturbance, such as human bacteria near sewage outlets), and morphological characteristics of marine species (such as the weight and lipid content of the food storage organ in sea stars and sea urchins) have also been shown to be indicative of organic waste pollution in Antarctica. Environmental bioindicators are therefore typically applied to demonstrate or monitor localized or point source contamination, and the measurement variable of interest is generally the physiological status of individuals, their organs, or their body tissues.

Ecological bioindicators are species or species groups that demonstrate the impact of either biotic or abiotic stressors on the biodiversity or ecology of a system. In ecological bioindication the fates of the bioindicator species are often themselves of concern, and population and community parameters are the targeted measurement variables. In Antarctica, populations of predatory marine mammals and birds have been used as ecological bioindicators to monitor the ecosystem impacts of harvesting marine resources. In particular, population parameters such as the breeding population size, breeding success, and adult body mass of penguins and seals are used as ecological bioindicators of the effect of large-scale fishing on Antarctic marine ecosystems. Changes in community measures, such as the species richness and composition of marine benthos, have also been demonstrated to be indicative of the impacts of disturbance on Antarctic biodiversity and ecology. Potential ecological bioindicators of climate change in Antarctica include activity thresholds in terrestrial microalgae; the abundance and distribution of plants; and arthropod population size, life cycle duration, geographic range, and body water status.

Finally, biodiversity indicators are higher-level taxa, such as orders, families, or classes, that are well known and therefore used as surrogates for wholesale patterns in species richness. Biodiversity indication has been little applied in Antarctica, possibly because of the low terrestrial species richness and consequently the small need to estimate patterns of biodiversity. However, in the marine environment the species richness of comparatively better-known taxa such as the Crustacea have been used to examine patterns of biodiversity across Antarctic marine subsystems. Moreover, in the more diverse sub-Antarctic, the species richness of native and alien mammals, birds, insects, and vascular plants was used to identify the set of islands that best represent sub-Antarctic biodiversity and are of the highest conservation value.

Regardless of the category of bioindication concerned, a rigorous bioindicator selection and testing process is critical. The essence of bioindication is the confidence with which a bioindicator may be used to provide an accurate reflection of environmental state. While there are some generic properties for good bioindicators, for example that they are time- and cost-effective to sample, the characteristics of a suitable bioindicator largely depend on both the category of bioindicator being selected and the case-specific bioindication objective. This objective, as well as the context within which the bioindicator is to be applied, must be clearly defined at the outset. The testing of potential bioindicators involves establishing a significant, strong, and predictable relationship between the bioindicator and biotic or abiotic stressor of interest. This is achieved by using appropriate sampling methods and standard sampling design principles. It is particularly important to be able to distinguish between natural variation and the disturbance-induced bioindicator response. This is followed by independent testing of the bioindicator within the spatial or temporal context within which it is to be applied. Repeated testing in this way results in the development of robust bioindication systems (decision-making tools for extracting environmental information and for application in monitoring and environmental-impact assessment), with quantified confidence limits for their application.

While the initial identification of suitable bioindicators and the development of bioindication systems may be costly and time-consuming, without this investment it is not possible to establish the degree of certainty necessary for the successful application of a bioindicator. Nonetheless, much data may be gathered during the process of monitoring, and monitoring is therefore used to confirm the efficacy of bioindicators as well as to refine and improve the predictability of bioindication systems. Because of the sensitivity of Antarctic and sub-Antarctic systems to environmental change, particularly climate, the region is highly suited to monitoring programmes that examine the consequences of such change. Such monitoring programmes must necessarily include bioindicators as representatives of the changes occurring. Antarctica faces continued threat from biotic and abiotic changes associated with human activities and impacts. Bioindicators are therefore an increasingly essential component of environmental assessment programs for the conservation of the continent and its surrounding islands.

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See also **Biodiversity, Terrestrial; Ecotoxicology; Pollution**

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BIOLOGICAL INVASIONS

Every day huge numbers of species are on the move to new localities around the world. This is of great importance, as introduced species are widely considered as one of the biggest threats to biodiversity and ecosystem functioning. For tens of millions of years Antarctica, its outlying islands, and the Southern Ocean have been isolated by "barriers": mainly surrounding deep water, the Antarctic Circumpolar Current (ACC), and the Polar Frontal Zone (PFZ). Yet as elsewhere on Earth, microbes and macro-organisms (i.e., plants and animals) have been transported into southern polar lands, lakes, and sea. The time context of this is important; organisms have, on numerous occasions, been bulldozed into small pockets of land (terrestrial species) and to the edges of the shelves (marine species) by expanding ice sheets. Such expulsions have then been followed by periods of reinvasion as the ice sheets retreat. However, until recently, colonisation of deglaciated land and ice-shelf retreat have probably been by polar species rather than those from other oceans and continents. So species have almost certainly been arriving and departing by a number of "natural" methods for millennia, but in the last ~200 years there have been a large number of invaders establishing—particularly on sub-Antarctic islands. Before human activity around the southern polar region, microbes and plant or fungus propagules would still have been arriving as airborne particles. Potential invaders amongst marine species could be carried on currents or hitchhike on floating volcanic rock (pumice from volcanism), driftwood, kelp, or megafauna (e.g., barnacles attached to fur seals). Floating rock travelled to New Zealand from the 1963 eruptions in the South Sandwich Islands and *Nothofagus* tree trunks have floated south across the PFZ to wash ashore on Antarctic shores. Additionally, there is evidence of species travelling passively into and out from Antarctica, but concern over introductions focusses on the most recent and anthropogenically mediated species transport for two reasons. First, the rate of introductions, number of mechanisms, and types of organism able to travel to Antarctica have all increased in association with humans. Second, climate change has rapidly changed, and is likely to further change, the survival and establishment prospects of invaders.

In the last 2 centuries, humans have travelled deeper and more frequently into Antarctic waters. In the last decade alone the numbers of tourists and ships travelling to the Antarctic have both quadrupled. Large numbers of propagules, such as seeds, spores, and even invertebrates, can be present on the walking boots of just one tourist. With humans have been a wave of deliberately or accidentally introduced species, including many vascular plants, worms, insects, mites, and mammals. In the sub-Antarctic islands, deliberate terrestrial introductions have included species imported for food, pleasure (pot plants), to control other introduced animals, or during scientific transplant experiments. Accidental introductions have accompanied many of those which were deliberate, but in addition have arrived on ships and aircraft as well as on human clothes. At two of the best-studied localities, Marion Island (in the Prince Edward Islands) and Îles Kerguelen, there have been 33 and 111 known terrestrial introductions. A few islands, however, remain near pristine with no nonindigenous species recorded (e.g., McDonald Islands). In fresh water, several species of salmonid fish have been introduced (particularly to Îles Kerguelen) and some crustaceans may have been, but the origin of lakes and stream biota has been little studied to date. The human link to most sub-Antarctic species introductions is reflected in the distributions and abundances of established alien plants and many insects which centre around whaling stations, research stations, and other heavily visited sites. Many invaders have persisted in the sub-Antarctic islands, and at Signy Island, in the maritime Antarctic, both an introduced midge and nematode have been established. There is little evidence to date of invaders successfully establishing on the continent of Antarctica; however, new micro-algae are persisting around Scott Base on the edge of the Ross Ice Shelf. Typically biodiversity in terrestrial systems is low so that just a few aggressive introduced species can have a dramatic influence. At Marion Island nearly 40% of the springtail community are invaders. An inevitable consequence of invaders becoming established is a "homogenisation" of faunas around the world and a loss of native biodiversity. Although many invading species are temporarily or permanently benign, some are serious competitors for food or space with native species, and others directly eat native species.

On Marion Island an intense eradication programme seems to have been successful in removing one prominent introduced predator, the cat, a species which has caused particular damage to nesting bird populations on sub-Antarctic islands. Further south, the Poa grass that invaded Deception Island was eradicated by an eruption. Further south still, on the continent, the midge, which persisted for several years in the sewer system of an Australian Antarctic research station, was finally eradicated after a deliberate campaign. Most of the terrestrial aliens identified to date have been found to be European. Only recently have scientists even started looking for invaders or mechanisms of invasion in the marine environment around Antarctica. It seems likely that marine species transport by shipping is most likely to be out of Antarctica in ballast water and in by hull fouling. This is because (1) ships travel south into the Southern Ocean after visits in temperate ports where they could easily pick up invasive species (ports are hotspots for many such species), and (2) typically after unloading in Antarctica, ships take on ballast water for the journey northward. Several invasive species (e.g., the sea squirt *Ciona intestinalis* and the bryozoan *Watersipora subtorquata*) have even been found on the hulls of ships. Marine species have been found rafting on kelp and plastic, and giant spider crabs are being discovered further and further south with each year of sampling. Nonnative marine crustaceans have been discovered—two as larvae and another as an adult—in the South Shetland Islands. There is no indication, however, that any of these has become established or even reproduced; thus, the Southern Ocean remains the only major environment on earth with no known established invaders.

Climate change is changing the context of invasions. Air, soil, and lake temperatures have all increased rapidly (more so than anywhere else except in parts of the arctic), which has drastically changed survival prospects of propagules arriving in terms of their hardiness, length of growing season, and water availability. This is most obviously demonstrated by manipulative experiments whereby small areas of land are maintained at slightly higher than ambient temperatures by positioning small translucent plastic greenhouses over them. The survival of propagules and growth of plants is remarkably different to adjacent areas and visually striking. In the marine environment sea-surface temperatures are also predicted to increase. Although the error associated with model estimates is large, values as high as ~2°C are suggested (total annual variability of sea surface temperature is <4°C at most localities and <1°C at some). Such a rise should both increase the viability of cold temperate invaders and place many native species close to functional maximum temperatures.

David K. A. Barnes

See also **Circumpolar Current, Antarctic; Deep Stone Crabs; Kerguelen Islands (Îles Kerguelen); Marine Debris; Prince Edward Islands; Polar Front; South Sandwich Islands**

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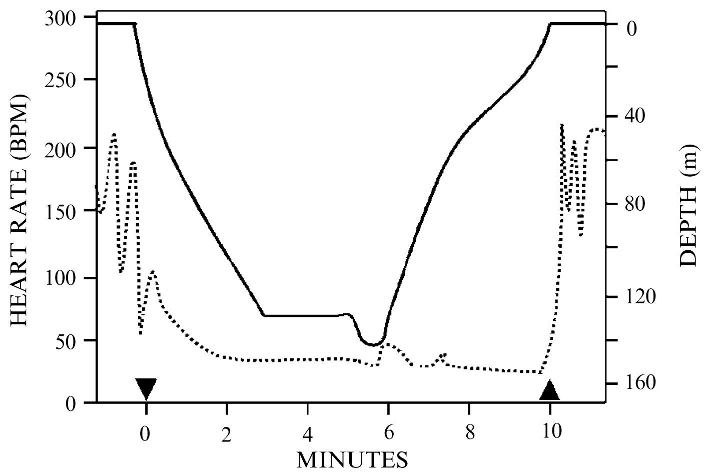
BIRDS: DIVING PHYSIOLOGY

Within the province of the Southern Ocean, there are four distinct groups of diving birds. They are penguins (family Spheniscidae); diving petrels (Pelecanoididae); petrels, shearwaters, prions, and fulmars (Procellariidae); and cormorants (Phalacrocoracidae). The most fully adapted for diving are the flightless penguins. Externally, their wings have evolved to short flippers with scale-like feathers covering the skin, and a nearly perfect hydrodynamically streamlined body. Highly modified feathers add further to the reduction of drag, in addition to waterproofing and insulation. Internally, they have exceptionally large pectoral muscles that are about 25% of the total body mass, and these same muscles have extreme concentrations of myoglobin, an oxygen-binding molecule.

Among the seventeen species of penguins the most exceptional diver, and one of the most studied with regard to diving adaptations, is the emperor penguin *(Aptenodytes forsteri)*. With an adult body mass ranging from 25 to 40 kg, it is the largest of all diving birds. With size often come greater diving capacities, and the emperor penguin holds the record for maximum diving depth (to 560 m), and also the longest dive duration for any bird (22 min). How this species responds to such extremes in breath-holding and water pressure is intriguing, and the answers will help to explain the adaptations to diving in all aquatic birds, most of which are much less suitable for study.

The close association of emperor penguins to the Antarctic sea ice, their willingness to dive under the ice, and their body size make possible an experimental procedure related to diving that would not be possible otherwise. Emperor penguins diving freely through a remote hole in the sea ice are obliged to return to the same hole to breathe and exit the water. Under these circumstances, physiological responses have been recorded with a variety of sensors attached to the penguin and connected to a submersible microprocessor. In addition, both emperor and king penguin *(A. patagonicus)* adults nurturing chicks have had similar recording devices attached when they go to sea to obtain food for their chicks. During these foraging trips they may travel several hundred kilometers before returning to the chicks.

A bird diving to depth responds to three major gas-exchange effects: (1) a cessation of an external oxygen supply resulting in hypoxia; (2) an increase in external pressure to as much as 57 atmospheres, in the case of the emperor penguin; and (3) a reduction in the insulating properties of the feathers. The results of experiments in which recorders have been attached show the responses to some of the basic effects of diving to depth. For example, as the level of hypoxia increases



The change in heart rate during the course of a dive to a depth of 130 m. The upside-down and upright solid triangles indicate the beginning and end of the dive. The solid line is the depth, and the dashed line is the heart rate. (Figure modified from P. Ponganis, unpublished data.)

during an extended dive of 10 min to a maximum depth of 130 m, the figure above shows the cardiac response. The heart rate drops from a predive hyperventilation rate of over 200 beats min^{-1} (BPM) to 50 BPM within 2 min after the start of the dive. The rate decreases a further 10 BPM after a further 2 min, where it remains until the end of the dive, 6 minutes later. Other important changes are occurring simultaneously. From the surface to about 20 m depth, the bird strokes vigorously to overcome the positive buoyancy of the air trapped in the feathers and gas contained in the internal air sacs. With increasing depth, hydrostatic compression reduces the air and gas volumes within the feathers and air sacs and the stroke frequency of the wings is reduced as the compression reduces the positive buoyancy provided by these air spaces. With this reduction in wing beat frequency, the work of swimming decreases, as does the rate of oxygen consumption from the body oxygen stores. With compression of the internal air sacs, the oxygen and nitrogen pressures increase and these gases are more readily passed to the blood, where they are transported to various parts of the body. However, the reduced heart rate modifies blood distribution, from widespread flow to all organs while the bird is at the surface to a more restricted distribution. This lessened transport of oxygen conserves some of the onboard stores, presumably for organs such as the brain that have a low tolerance to oxygen deprivation. Muscle has a high tolerance for hypoxia and also has a large amount of oxygen bound to myoglobin, which it can use internally. Simultaneously, the nitrogen level of the blood is rising, and this could be a liability if the concentrations were to reach a level that might induce a narcotic effect in the brain. Also, as the bird ascends, bubble formation in the blood and tissues might occur if nitrogen reached a high tension while the bird was at depth. Considering the debilitating effect of gas bubble formation, also called decompression sickness or "the bends," it is unlikely that diving birds are plagued by this risk. How a diving bird avoids exposing itself to high tissue nitrogen concentrations during a dive is still unknown.

Another mystery is the management of oxygen stores. Most dives are within the limits of the aerobic diving capacity that the onboard oxygen stores provide. This aerobic diving limit (ADL) can be estimated if the body oxygen stores and the diving metabolic rate are known. For the several species of penguin in which the stores and consumption rate have been estimated, it has been found that most dives are within this predicted ADL. However, many are not, and some of these dives seem to be very important to the foraging ecology of the bird. The 10-minute dive is double the predicted ADL of the emperor penguin. Dives of this duration and to even much greater depths are common, and clearly important to the bird. Possibly for some dives the ADL is extended by some altered responses to breath-holding, different from those that are more often observed for more shallow dives. For example, it has been shown that within the body there are regional differences in temperature that suggest the metabolic rate of some organs may be lowered to minimal levels during some extreme dives. Changes in buoyancy with depth may also reduce swim effort and allow the bird to glide more while descending. These and other adaptations to deep diving still need to be examined in greater detail.

Jerry Kooyman

See also **Antarctic Prion; Cormorants; Diving—Marine Mammals; Emperor Penguin; Penguins: Overview; Shearwaters, Short-Tailed and Sooty; Southern Ocean**

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BIRDS: SPECIALLY PROTECTED SPECIES

Since the signing of the Antarctic Treaty and the establishment of the Antarctic Treaty System in 1959, a high level of conservation has existed in the Antarctic region south of 60°S. The 1964 Agreed Measures for the Protection of Antarctic Fauna and Flora represented the earliest formal mechanism for the protection of native Antarctic species. Specially Protected Species were established under the Agreed Measures and presently comprise all fur seals of the genus *Arctocephalus* and Ross seals *(Ommatophoca rossii)*. No birds had been designated as Specially Protected Species as of 2005; however, discussions are underway regarding possible additions to the list.

Measures for the protection of Antarctic flora and fauna have been subject to review and improvement. The 1991 Protocol on Environmental Protection to the Antarctic Treaty (the Madrid Protocol) simplified and formalised early recommendations of the Antarctic Treaty System to bring Antarctic conservation in line with developments in international environmental law over the period 1970–1990.

Annex II of the Madrid Protocol is based largely upon the Agreed Measures, which were superseded by the Madrid Protocol when it entered into force in 1998. Annex II prevents the taking of or harmful interference with native fauna and flora unless in accordance with a permit. Permits are allowed for scientific research or educational purposes, such as the collection of specimens for museums. Permits are subject to set conditions that aim to protect the ecological integrity of the region and ensure that methods used to take native fauna cause minimal pain and suffering.

Specially Protected Species are subject to the same conditions as other native flora and fauna, but there are additional measures in place for their conservation. Specially Protected Species may only be taken if the taker is in possession of a permit for compelling scientific research. Killing Specially Protected Species is discouraged, and Treaty Parties are advised to minimise the number taken or killed to ensure the long-term survival and recovery of Specially Protected Species.

Annex II is currently under review. The Scientific Committee on Antarctic Research has been asked to advise the Committee on Environmental Protection on possible deletions/additions to Specially Protected Species; a process and criteria for Specially Protected Species listing/delisting; and practical means for their protection. The Intersessional Contact Group on the Annex II review has discussed the application of World Conservation Union (IUCN) Red List criteria to fauna and flora breeding or occurring in the Antarctic. The following table describes Antarctic birds by their conservation status.

Numerous proposed changes to Annex II are being discussed. Recommendations regarding Specially Protected Species measures currently include theautomatic listing of Endangered species; need to assess the conservation requirements of Vulnerable species; necessity for a regional assessment of the conservation requirements of Antarctic fauna and flora; development of Specially Protected Species criteria and a designation process to ensure that Specially Protected Species listings/delistings are supported by scientific evidence; taking of Specially Protected Species for compelling scientific or conservation reasons.

The Committee for Environmental Protection made recommendations at the 2005 Antarctic Treaty Consultative Meeting regarding amendments to Annex II based upon the advice obtained by the Scientific Committee on Antarctic Research and the Intersessional Contact Group.

Jane Harris

Antarctic Birds by IUCN Conservation Status

Common Name and Scientific Name	IUCN Status*
Avifauna breeding south of 60° South	
Southern giant petrel *Macronectes giganteus*	Vulnerable (VU)
Macaroni penguin *Eudyptes chrysolophus*	Vulnerable (VU)
Gentoo penguin *Pygoscelis papua*	Lower Risk/Near Threatened (NT)
Avifauna found but not breeding south of 60° South	
Amsterdam albatross *Diomedea amsterdamensis*	Critically Endangered (CE)
Northern royal albatross *Diomedea sanfordi*	Endangered (EN)
Black-browed albatross *Thalassarche melanophrys*	Endangered (EN)
Indian yellow-nosed albatross *Thalassarche carteri*	Endangered (EN)
Sooty albatross *Phoebetria fusca*	Endangered (EN)
Rockhopper penguin *Eudyptes chrysocome*	Vulnerable (VU)
Wandering albatross *Diomedea exulans*	Vulnerable (VU)
Salvin's albatross *Thalassarche salvini*	Vulnerable (VU)
Southern royal albatross *Diomedea epomophora*	Vulnerable (VU)
Grey-headed albatross *Thalassarche chrysostoma*	Vulnerable (VU)
White-chinned petrel *Procellaria aequinoctialis*	Vulnerable (VU)
Eaton's pintail *Anas eatoni*	Vulnerable (VU)

Critically Endangered: facing an extremely high risk of extinction in the wild in the immediate future. Endangered: facing a very high risk of extinction in the near future. Vulnerable: facing a high risk of extinction in the wild in the medium-term future. Lower Risk/Near Threatened: not conservation dependent but close to qualifying as vulnerable.

See also **Antarctic Important Bird Areas; Antarctic Treaty System; Conservation of Antarctic Fauna and Flora: Agreed Measures; Protocol on Environmental Protection to the Antarctic Treaty; Scientific Committee on Antarctic Research (SCAR)**

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BISCOE, JOHN

The achievement for which John Biscoe's name will remain immortal was the third circumnavigation of Antarctica, which he accomplished in 1830–1832. During this epic, Biscoe (1794–1843) made "persistent efforts to explore" the South Sandwich Islands, discovered a new section of the continental coast, Enderby Land, and charted a significant part of the western side of Graham Land, discovering Adelaide Island and other islands in the process. He also made observations on the wildlife, air and water temperatures, the aurora, compass variations, and the winds close to the continental coast.

His two predecessors, James Cook and Fabian von Bellingshausen, commanded government expeditions, but Biscoe's was privately arranged, by the well-known London firm Enderby Brothers. They were keenly interested in exploration and the intention was that the expedition should be exploratory and scientific, albeit with the aim of covering the costs by sealing when possible. It was, in comparison with its forebears, poorly equipped. The vessels were a small "hermaphrodite brig," *Tula,* and *Lively,* which was a mere Cowes pilot cutter. With a total crew in both ships of twenty-seven men and two boys, they were wholly inadequate for such a voyage. It is a testimony to the skilled and determined seamanship of Biscoe, who travelled on *Tula,* and of Captain George Avery, of *Lively,* which was frequently separated from *Tula,* that they survived at all, let alone achieved what they did.

After service in the Royal Navy, during which he reached the rank of Acting Master, Biscoe joined the merchant navy on the peace in 1815. He had good references from the captains he had served under, and was appointed by Enderby Brothers to command the expedition even though he may never have been in command before and seems never to have visited the Southern Ocean nor to have undertaken a sealing or whaling voyage.

The expedition left London on July 10, 1830, and, after a difficult passage, which exposed the limitations of the ships, it arrived at the Falkland Islands on November 11. The ships departed on November 27, and their first achievement was to eliminate the fabled "Aurora Islands" (also searched for by James Weddell) from the chart by sailing over their position. Biscoe then reached the eastern side of the South Sandwich Islands on December 19. He spent the period from then to New Year's Day 1831 navigating through the archipelago, and often sent *Tula*'s small boats and *Lively* to examine the islands more closely. This was to no avail as far as landing places or seals were concerned, but many important observations were made, particularly relating to the islands' positions. Biscoe then headed southeast, crossing the Antarctic Circle on January 21, 1831, and reaching his farthest south, 69° S, on January 28. Further progress was blocked by pack ice, with what is now Princess Astrid Coast only 100 km away.

On February 24–25, Biscoe sighted the ice front near Tange Promontory and spent the next few weeks heading eastwards and attempting to survey the new land despite continuous gales and adverse winds and currents. He dutifully named many of the mountains after members of the Enderby family. By March, *Lively* had become separated from *Tula,* many of the sailors were sick, and the expedition was in serious difficulty: "The vessel is a complete mass of ice, only 3 of the crew who can stand" (Biscoe 1830–1833). Biscoe resolved to head for Tasmania, and *Tula* arrived at Hobart on May 9, 1831. The crew were assisted in mooring the ship by the pilot and by men from Eliza, commanded by Weddell, which was in port. Biscoe assumed that *Lively* had foundered in a storm, but when *Tula* departed in early September, much to Biscoe's surprise, it hove in sight. On separation, Avery, appreciating that his ship was in a desperate position concerning the health of the crew, had headed for Port Phillip, where they had arrived "in the very utmost state of distress" (Biscoe 1830–1833). Going ashore to secure provisions, the crew returned to discover *Lively* gone. They found the ship aground two weeks later, refloated it, and made for Hobart and the fortunate meeting with *Tula*.

Allowing time for *Lively* to be refitted, Biscoe set out again on October 8, 1831, heading for New Zealand. They attempted some sealing, on the Chatham Islands, but secured fewer than thirty skins. After eliminating the "Nimrod Islands" from the chart, again by sailing over their position, Biscoe resolved to visit the South Shetlands to undertake further sealing, but took a more southerly route than that direct to the archipelago. On February 15, 1832, land was sighted with lofty mountains. Biscoe named this Adelaide Island, after the consort of King William IV. He also observed the mountains of Bellingshausen's Alexander Island, some 160 km to the south. Biscoe examined the west coast of Graham Land as closely as circumstances permitted, discovered the Pitt Islands (now named the Biscoe Islands), and landed on what is now Anvers Island. Believing this to be the mainland, he landed and took possession of it. He was among the first to appreciate that these and his discoveries were "the headlands of a Southern Continent" (Biscoe 1830–1833).

Proceeding northwards, the ships arrived at the South Shetlands and added slightly to their meagre catch of skins and oil. It was late in the season, and by this date the seal population of the islands had effectively been destroyed. Therefore, Biscoe resolved to head for the Falklands, where both ships arrived on April 29, 1832, thus completing their circumnavigation.

Unfortunately, *Lively* was wrecked there, and Biscoe had trouble with the crew, who did not want a renewal of the voyage "for which I can hardly blame them" (Biscoe 1830–1833). He therefore headed north. There was much desertion in Brazil, and with a depleted crew *Tula* arrived in London on February 8, 1833. The voyage had been a financial disaster for the Enderby family, but they could at least bask in the glory of its achievements. These were speedily delivered to the Royal Geographical Society, and Biscoe was awarded the Society's gold medal as well as an equivalent from the French.

Biscoe returned to the sea and undertook voyages in Australian waters including a possible one to 75° S, although this must be regarded as doubtful. By the 1840s, he was seriously ill, and indeed his constitution never recovered from the damage it received on the great voyage. Charitable solicitations were made in the Tasmanian press to enable him and his family to return to England. En route he died and was buried at sea.

Biscoe's discoveries rendered more likely the existence of an Antarctic continent, and his observations of the coasts along which he travelled were, in the circumstances, very accurate. His discovery that the usual wind, close to the continent, was from south through east led him to suggest that future efforts should be from east to west. It was this seminal proposal that placed those expeditions following him most deeply in his debt.

Ian R. Stone

See also **Bellingshausen, Fabian von; Cook, James; Enderby, Messrs.; Sealing, History of; South Sandwich Islands; Weddell, James**

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BLACK-BROWED ALBATROSS

The black-browed albatross *(Thalassarche melanophrys)* is a medium-sized albatross weighing between 3 and 5 kg and with a wing span of over 2 m. Adults are distinguished by a white head with distinctive black brow above the eye, a bright yellow-orange bill, and an underwing pattern with a broad black leading edge. Juveniles have dark horn-coloured bills with dark tips.

In 2000, black-browed albatrosses were listed as "near-threatened," with this listing being upgraded to "vulnerable" in 2002. The conservation status of black-browed albatrosses was again upgraded in 2003 to "endangered," as it is inferred that the global population will have decreased over 50% over the three generations (65 years) on the basis of recent rates of population decreases. Black-browed albatrosses are the most widespread of all albatross species, breeding at twelve sites around the Southern Ocean. About 60% of the global population of 530,000 breeding pairs breed at the Falkland Islands. Other large populations occur at South Georgia and Chile, with the smallest populations occurring at Macquarie Island and Campbell Island.

Black-browed albatrosses breed colonially on tussock slopes or on cliff terraces. Breeding generally occurs annually, regardless of breeding success the previous season, and the breeding season extends from September to April. Eggs are laid in October and incubated for about 68 days. After hatching the parents continue to alternate the brood guard shifts for about 3 weeks. The chicks fledge about 4 months after hatching, with chicks and successful breeding adults departing the colonies in April or May.

Typically, immature birds return to the colonies at 6–7 years of age, and breeding usually begins when birds are 10 years of age. The life history of black-browed albatrosses at South Georgia is well studied, and for this population, it is the very low survival rate of juveniles that has the most influence on the population decrease.

Black-browed albatrosses occur throughout the Southern Ocean, reaching as far north as 20° S during the nonbreeding winter months, and usually between 40 and 70° S in summer. Comparison of satellite tracking information shows that black-browed albatrosses from different populations have largely mutually exclusive foraging ranges. Most breeding birds forage extensively over shelf, or shelf-break waters, in many cases close to their colonies. Some birds, however, travel considerable distances to forage and visit the Polar Front waters and waters adjacent to the Antarctic ice edge.

Black-browed albatrosses feed by both surface seizing and diving to depths of 4 m. Consistent with their variety of foraging habitats, their diet includes fish, squid, and krill and shows distinct variation with location, with more squid being consumed by birds when foraging at frontal zones or in deeper ocean water.

These birds are also energetic and consummate scavengers of bait and offal discards from fishing vessels. It is this practice of scavenging baits from longline hooks that results in the deaths of more than 300,000 seabirds, including an estimated 100,000 albatrosses and petrels, each year in both legal and illegal fishing practices. Black-browed albatrosses are among the species of albatrosses killed on longlines, and this has been identified as a key factor driving the population decreases. In the absence of the adoption of effective changes to fishing practices, it is projected that such decreases will continue into the future.

ROSEMARY GALES

See also **Albatrosses: Overview; Campbell Islands; Fish: Overview; Macquarie Island; Polar Front; Seabird Conservation; Seabird Populations and Trends; Seabirds at Sea; South Georgia; Squid; Zooplankton and Krill**

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BLUE WHALE

Blue whales are of the order Cetacea, suborder Mysticeti (meaning moustache, which refers to baleen plates), family Balaenopteridae, and genus and species *Balaenoptera musculus* (Linnaeus 1758). "Balaenoptera" comes from the Latin for "winged whale," while "musculus" is latin for "muscle." Two subspecies are found in the Antarctic, the true blue whale, *B. m. musculus*, and the pygmy blue whale, *B. m. brevicauda*. The pygmy blue whale was not identified until the early 1960s. Other common names used in the past include "sulphur-bottom" and "Sibbald's rorqual."

General Appearance and Size

Blue whales are the largest animals ever to have lived. In the Southern Hemisphere, the average true blue whale female reaches about 25–26 m in length and weighs around 100–120 tonnes. Females are generally about 5% longer than males. The largest recorded blue whale measured 33.6 m, perhaps weighing as much as 190 tonnes. Pygmy blue whales are smaller, as their name implies, reaching about 22 m.

The blue whale has a large, broad head that comprises around 25% of the total body length. A head ridge runs to the paired blowholes, which are located behind a characteristically large "splash guard." The "blow" is tall (up to 12 m), dense, and broad and is helpful in identifying the species from a distance. The mottled skin can appear blue but is generally pale and dark grey. The ventral surface is lighter. Chevron-like patterns curve down and back on both sides behind blowholes. The patterns on the skin can be used to identify individuals. The dorsal fin is relatively small and is set so far back on the body that it does not become visible for some time after the head breaks the surface. Blue whales are rorquals, and have 60–88 ventral grooves that run from the lower jaw to the umbilicus and that allow the mouth to expand when feeding. They have 270–395 triangular black baleen plates hanging from the upper jaw on each side (about 1 m in length and 0.5 m at the widest part), spaced 1–3 cm apart, used in filtering krill. The bristles on the inner side are around 0.3 mm in diameter. The relatively blunt flippers reach about 15% of body length and are dark grey on top and pale underneath. The gray flukes are broad and triangular with a straight or slightly curved trailing edge and they may have variable white patches on the underside.

In Antarctic waters, all or portions of the body may have a dark yellow-green to brown sheen from the presence of diatoms, single-celled algae that attach themselves to the skin and are the origin of the common name "sulphur-bottom."

Distribution and Migration

True blue whales are found throughout the Southern Hemisphere (and indeed, the Northern Hemisphere), although densities are lower in the eastern Pacific sector. They migrate between sub-tropical breeding areas (the location of the breeding grounds is unknown) and the Antarctic feeding grounds, where they are found primarily close to the ice edge. Blue whales rarely, if ever, feed outside the Antarctic and so, in the 4–5 months (November to March) they are in the Antarctic, they must store energy in their blubber to last them for the migration to and from the breeding grounds, as well as their time on the breeding grounds. Pygmy blue whales generally do not migrate as far south as true blue whales, with most animals found north of 55° S. There are probably at least six separate populations of true blue whales in the Southern Hemisphere.

Life History and Behaviour

Blue whales can live up to 100 years old. True blue whales reach sexual maturity at around 23–24 m (females) and 22 m (males) and probably at about 8–10 years old. Pygmy blue whales reach sexual maturity at around 22 m (females) and 21 m (males). The gestation period is thought to be around 12 months; newborn calves weigh 2–3 tonnes and measure about 7 m (true) or 6.3 m (pygmy). They are weaned at about 6 months, by which time they have reached around 13 m (true) or 11 m (pygmy). There is evidence that pregnancy rates increased and animals reached sexual maturity earlier after depletion by whaling, perhaps as more food per individual became available.

Little is known about the social structure of blue whales. They are usually seen as single animals, although larger concentrations (up to fifty animals) are known in areas of high prey density (the primary prey species is Antarctic krill, *Euphausia superba*). Blue whales can engulf up to 32 m^3 of water and prey with the ventral grooves fully distended and eat up to 6 or more tonnes of krill per day. Feeding blue whales typically dive for around 8–15 minutes whilst feeding.

It is interesting that, at least in the Northern Hemisphere, blue whale/fin whale hybrids have been documented; in at least one instance the female (a fin whale) was pregnant.

Blue whales produce extremely powerful, low-frequency (17–20-Hz) sounds that may be able to travel hundreds or even thousands of kilometres. It is thought that these sounds may play an important role in communication and perhaps navigation.

Conservation/Status

Blue whales were the preferred target of commercial whalers in the Antarctic because of their large size and hence high oil yield. The populations were severely depleted but not given complete protection by the International Whaling Commission until 1966. Illegal catches by the Soviet Union (largely of pygmy blue whales) continued until the beginning of the 1970s. About 358,000 blue whales were killed south of 40° S between 1904 and 1970, with over half of these killed between 1929 and 1939.

Although still at very low levels (less than 1% of their original numbers), true blue whales are showing encouraging signs that they might be recovering at around 2–8% per year. A recent study estimated their numbers in the Antarctic to be around 1700 in 1996.

Aside from man, the main predator of blue whales is the killer whale, *Orcinus orca,* which has been known to take adults as well as calves. Some scientists have suggested that interspecific competition with Antarctic minke whales *(B. bonaerensis)* may have inhibited the recovery of blue whales. The effect of climate change on stocks of krill and hence blue whales is unknown.

Rob Williams and Greg P. Donovan

See also **Diving—Marine Mammals; International Whaling Commission (IWC); Killer Whale; Minke Whale (Antarctic Minke Whale); Whales: Overview; Whaling, History of; Zooplankton and Krill**

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BOOKS, ANTARCTIC

The literature of the Antarctic had its beginnings in 1775 with the anonymous, surreptitious publication of John Marra's *Journal of the* Resolution*'s Voyage,* a firsthand account of James Cook's second voyage rushed into press a mere six weeks after the expedition's return, eighteen months before the 1777 publication of Cook's official account, *A Voyage towards the South Pole and round the World*. During that voyage, the Antarctic continent, while remaining undiscovered, was first circumnavigated, the Antarctic Circle was crossed for the first time, and all previously known lands were proven not to be part of the great, imagined "terra australis." Explorers had been probing farther and farther south for two centuries prior to the early 1770s, but all claims concerning an Antarctic continent were either misrepresentations or speculations.

Sealers, nearly all British and American, reached the vicinity of the Antarctic Peninsula in the years 1819–1830 but few cared about publishing their observations. The history of that period has only recently been pieced together by painstaking delvings into contemporary periodicals and what survives of records, logs, and charts.

By the end of the nineteenth century, still only a handful of Antarctic expeditions had set sail with serious scientific or hydrographic objectives: those of Cook, Fabian G. von Bellingshausen, James Weddell, John Biscoe, Jules S.-C. Dumont d'Urville, Charles Wilkes, James Clark Ross, Thomas Moore, Eduard Dallmann, Carl Larsen, Henryk Johan Bull, Adrien de Gerlache, and Carsten Borchgrevink. While more and more books and papers were making their way into print by the turn of the century, most concerning these voyages, only about seventy-five freestanding works and several hundred journal articles, had appeared.

Publications concerning the Antarctic became increasingly numerous during the 1890s and the first decades of the twentieth century in parallel with the evolving Heroic Age. Publishers almost everywhere during that period were manufacturing elaborately lettered, decorated, and illustrated cloth-backed, casebound books, often with foldout plates or maps, adding substantial appeal to the volumes that document this important and exciting period of Antarctic history-making. But with the exception of occasional bestsellers, Antarctic publishing was not particularly profitable. Even so, leaders' firsthand narratives sold at least satisfactorily, and trade publishers were willing to partner with explorer–authors. Some of the best-known London publishers took on Antarctic narratives, including the firms of John Murray (Ross); Smith, Elder (Robert Falcon Scott); Hurst and Blackett (Otto Nordenskjöld); William Heinemann (Shackleton, Douglas Mawson); Hodder and Stoughton (Jean-Baptiste Charcot); and Cassell (Frank Wild, Vivian Fuchs). In a notable instance, London publisher George Newnes financed the Borchgrevink expedition in exchange for future publishing rights to the official narrative. Explorers' profits from book sales were often applied to offset expedition debts, as in the case of Shackleton's 1907–1909 and 1914–1917 expeditions. Still, editions were often small owing to limited demand, with the result that many important books are nowadays hard to come by in their original editions. For example, Ross's two-volume set *A Voyage of Discovery* and *Research in the Southern and Antarctic Regions* (1847) was a classic in its own time, but only 1500 sets were produced.

Contemporary books by expedition participants other than the leaders, with the single exception of books emanating from Scott's last expedition, had virtually no demand and were printed in miniscule quantities by small publishing houses or by the authors themselves or their descendants. Apsley Cherry-Garrard's *The Worst Journey in the World,* concerning Scott's last expedition, has rarely been out of print since its first publication in 1922, while Leonard Kristensen's *Antarctic's Reise til Sydishavet,* a substantial Norwegian account of the Bull expedition, has never been translated. With the exception of Friedrich Bidlingmaier's little book *Zu den Wundern des Südpols,* no firsthand accounts or diaries of the German expeditions led by Drygalski and Filchner other than the leaders' have been published. Even these, long available in German, only appeared in English translation for the first time in 1989 and 1994, respectively. In some instances, leaders (Wilkes, Richard E. Byrd) suppressed the publication of participants' accounts.

Scientific works, with an even more severely limited audience coupled with an inordinate cost of producing the requisite illustrations or photographs, were usually underwritten by governments or scientific institutions with the aid of subscription, the creation of a dedicated scientific institution for ardent fund raising (William Bruce), or in the extreme, by selling off some of the expedition's prized collections of biological specimens and artifacts (Mawson). Johann Reinhold Forster produced *Characteres Generum Plantarum,* the botany of Cook's second voyage, at his own expense; the penalty for his effort was a substantial personal loss. The publication of Antarctic science has always been an extreme labor of organization and funding, writing and illustration, and publication and sales.

By the early twenty-first century, freestanding publications numbered several thousand and included not only expedition prospectuses, narratives (a number of which have become classics in the world's exploration literature), science reports, cartographic and photographic works, biographies and autobiographies, diaries and logs, analytical reviews, and bibliographies, but also interpretive works including art, poetry, literary prose, plays for screen and stage, treatises on leadership, and fiction. Journal articles number in the tens of thousands. The most recent two decades in particular have witnessed an explosion of new book publishing and the reissue of the classics coincident with surging Antarctic tourism and a worldwide mania for Antarctic heroes, particularly Ernest Shackleton. This energized market has unfortunately produced many items of negligible value, but serious historians and researchers have filled many gaps in knowledge concerning the classical and heroic periods, and expedition participants' diaries and English editions of heretofore-untranslated works are being published for the first time. And with technological improvements in image transfer, a number of fine illustrated books have appeared.

To navigate the literature, several bibliographies are available, which are given in the "References and Further Reading" list at the end of this entry. The principal strength of the first four is the extensive coverage of journal articles in multiple languages. Spence is a popular short list. Renard—strictly speaking an auction catalog, but valuable as more than that—represented a leap in Antarctic bibliographical scholarship, with multiple editions of individual works and brief, informative annotations. Rosove is a comprehensive analysis of freestanding publications concerning the classical and heroic periods, with extensive annotations. In addition to these bibliographies, several major polar research institutions' catalogs are available online.

Some of the great classics of the Antarctic literature are given in the "Great Classics of Antarctic Literature" list. Without a doubt, the *ne plus ultra* of the Antarctic literature is *Aurora Australis,* an anthology of writings by members of Shackleton's British Antarctic Expedition of 1907–1909, and the first book printed and bound in Antarctica. At least sixty-five copies were extant in 2005; certainly not more than ninety to one hundred were ever produced. Printed on a small press by novices to the trade and illustrated from etched aluminum plates under the adverse conditions of the Cape Royds hut in winter, then bound in plywood boards from packing cases, leather from horse harnesses, and string, the finished books were truly a remarkable achievement. Many books were signed by expedition members or carry an interesting provenance. Over half are in institutional libraries, leaving relatively few in private hands. When a copy fleetingly appears on the market, the would-be buyer must be prepared to pay upward of £30,000. Forty years ago, £300 would have sufficed.

MICHAEL H. ROSOVE

See also **Bellingshausen, Fabian von; Biscoe, John; Borchgrevink, Carsten E.; British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); British Antarctic *(Nimrod)* Expedition (1907–1909); British Antarctic *(Southern Cross)* Expedition (1898–1900); British Antarctic *(Terra Nova)* Expedition (1910–1913); Bruce, William Speirs; Byrd, Richard E.; Charcot, Jean-Baptiste; Cook, James; De Gerlache de Gomery, Baron Adrien; Dumont d'Urville, Jules-Sébastien-César; Fuchs, Vivian; German South Polar *(Deutschland)* Expedition (1911–1912); German South Polar *(Gauss)* Expedition (1901–1903); Imperial Trans-Antarctic Expedition (1914–1917); Larsen, Carl Anton; Mawson, Douglas; Nordenskjöld, Otto; Ross, James Clark; Scott, Robert Falcon; Shackleton, Ernest; Sealing, History of; Weddell, James; Wilkes, Charles; Wild, Frank**

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BORCHGREVINK, CARSTEN E.

Determining the contributions of Carsten E. Borchgrevink (1864–1934) to polar history requires a certain degree of patience and understanding. Certain facts about the work of Borchgrevink (pronounced "BORCH-gre-vink") are beyond dispute—he participated in the Antarctic expedition of 1894–1895 and led the Southern Cross expedition of 1898–1900. Assessing what he accomplished is not as simple.

An Anglo-Norwegian who went to Australia to seek his fortune but, instead, drifted through a variety of jobs including teaching, Borchgrevink made his entrée into the polar realms when H. J. Bull (1844–1930) used his connections to Sven Foyn (1809–1895), the inventor of the whaling gun, to launch a whaling expedition in Antarctic waters south of Australia. Bull wanted to take a scientist on this voyage of the Antarctic and might have enlisted the services of William S. Bruce (1867–1921), destined to be, arguably, the finest scientist–explorer the British produced in the Heroic Era. Alas, Bruce could not arrange to meet the ship's sailing date. Borchgrevink applied for the scientist's position but was rejected; instead, still enthusiastic for the voyage, he signed on before the mast.

The journey was not commercially successful but did contain one important incident—the first popularly recognized landing on the Antarctic continent. On January 23, 1895, a small boat approached shore with Bull, the ship's captain, Leonard Kristensen, and several others including Borchgrevink, who, as the ship neared land, leaped from the boat, either to guide it to shore or to claim, as he subsequently did, that he was the first person on the last continent.

Dubious though this claim was, Borchgrevink parlayed it into a career as an Antarctic explorer. Later that year he returned to Great Britain and addressed the International Geographical Congress meeting in London and electrified his audience with his first-hand experience of having seen Antarctica. While other aspects of his presentation caused some of the geographers present to be hesitant in their appraisal of the brash young man, Borchgrevink used the same directness to appeal to Sir George Newnes, a newspaper magnate, who agreed to fund an Antarctic expedition under Borchgrevink.

That effort, the Southern Cross expedition, for good and ill, established Borchgrevink's reputation in polar annals. The Anglo-Norwegian showed great skill in assembling a crew, materials for the expedition, and his scientific staff, but proved a failure as a leader in the field. His staff's amusement at their leader's gaffes and lack of scientific expertise soon turned to outright detestation of his whole being.

What sealed Borchgrevink's reputation was his inept handling of the scientific results of the expedition. At the minimum his carelessness destroyed much of the fine work of the scientists under his leadership; at worst he might have been encouraged in his behavior by jealousy of their accomplishments. Uncovered for these actions, he chose the route of the minimally competent administrator—blaming everyone but himself for problems he had created and lashing out at those who called him to task for his behavior.

After the expedition, Borchgrevink resumed the anonymity of his pre-1894 days, only occasionally coming to the public eye. He proposed to lead an expedition to the South Pole using reindeer in 1909, and, after the tragic end of Captain Robert Falcon Scott, reported to the press that Scott had confided to him his sense that he, Scott, would not return from the Terra Nova expedition. That claim is not substantiated.

Denied official recognition of his Southern Cross accomplishments because of the enmity of those in official British geographical circles, he was ignored until, in 1930, the Royal Geographical Society awarded him the Cullinan Medal for his accomplishments. By that time, the earlier animosity of his staff had tempered sufficiently that they endorsed this award.

Borchgrevink died in Oslo in 1934, a largely forgotten figure from a distant era of polar exploration.

T. H. BAUGHMAN

See also **British Antarctic *(Southern Cross)* Expedition (1898–1900); Bruce, William Speirs; Norwegian (Tønsberg) Whaling Expedition (1893–1895); Royal Geographical Society and Antarctic Exploration; Whaling, History of**

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BOUVET DE LOZIER, JEAN-BAPTISTE

Jean-Baptiste Bouvet de Lozier was born in Paris in 1705. His father, a lawyer at the Royal Council, came from a Breton family of St. Malo. Bouvet was a learned and refined man. He studied in Paris and wrote, "having seen a map of the world, I was stunned by this immense emptiness around the southern pole that geographers fill with unknown Lands, and at once was seized with the goal of discovering them." Sent to St. Malo, he was hired by the French East India Company, where he served as a shipmaster and later as a governor until the dissolution of the company in 1763.

Bouvet took an interest in the theories of the time about the location of the Land of Gonneville, then thought to be the southern continent. Indeed, a "Mémoire touchant l'établissement d'une mission chrétienne dans le troisième monde autrement appelé la Terre australe" ("Paper on the subject of the establishment of a Christian mission in the third world also known as Southern land") had been published in 1663 by the Abbé Jean Paulmier. Claiming to be a descendant of Gonneville, Paulmier recounted Gonneville's journey to what he had named the Southern Indias in 1503–1504. Also, Etienne de Flacourt recalled in his famous *Histoire de la grande île de Madagascar* ("History of the great isle of Madagascar"), published in 1661, this "continent a few weeks away" for which "Madagascar could be used as warehouse for trade."

Thus, Captain Bouvet offered (to the directors of the India Company) to go look for the mythical Land of Gonneville. He presented three papers, in 1733, 1735, and 1737, in which he argued the practical interest for East Indian trade of setting a base in the southern sea, the geographical knowledge of the southern sea, and, lastly, the beginning of a colonial power ("a new Europe is there for whom wishes to discover it," he wrote).

The India Company agreed, and in July 1738, two frigates, *Aigle* and *Marie,* under Bouvet's command, left the harbor of Lorient. As planned, they first stopped over in Brazil. Then, moving to the latitude of Patagonia in the south Atlantic, the frigates zigzagged from west to east of the Cape's meridian, between the latitudes of 44° S and 55° S, where the probable site of the discovery was thought to be.

As early as November 26, 1738, Bouvet wrote, "a fog arose that almost never left us, it is one of the greatest obstacles... More often the two ships could not see each other within the range of a gunshot." On December 31, the cold was intense and massive ice blocks loomed up through the fog and snow: "they took all sorts of forms, of islands, fortresses, ships; they lent themselves to all mirages, and the fantastical effects these floating and translucent masses would have been much more picturesque had the sun shone its rays on them. The sea was streaked by whales, divers, penguins, and albatrosses with a heavy and powerful flight."

On January 1, 1739, through gales, rough seas, thick fog, they glimpsed "a very high land that only the fog had prevented us from seeing earlier, it seemed covered with snow and surrounded by large ice masses."

This relief was named Cape Circoncision. But until January 12, any attempt to get closer to determine whether it were a cape of a southern continent or an island, was foiled by the fog, wind, ice, and exhaustion.

"We only saw on deck but a few sea officers and a few young seamen sustained by their honor or youthful strength, though all had lost almost all of their voice."

It was then that Bouvet decided to give up. It was a failure, and the southern continent seemed to withdraw farther and farther away toward the south, in unreachable seas. However, Bouvet wrote later, "if circumstances have since prevented that I employ myself to follow this undertaking whose success could be as glorious as useful to the State, at least I have the satisfaction to have been the first to propose it this century."

Today, Circoncision Cape remains: it is the northwest end of the Norwegian possession of Bouvetøya, located at 54°26′ S, 3°24′ E. What is remarkable is that Bouvet actually happened upon this pin-head in the midst of the vast Southern Ocean. Still, it would take almost four centuries to prove that Gonneville had not landed in 1503 on Antarctic land, but on the Brazilian coast, near Porto Alegre.

Bouvet later married the daughter of an administrator of the India Company, and in 1751 was named governor of Île Bourbon (known today as Réunion), later transferring to Île de France (Mauritius), both islands at the time belonging to the India Company. As governor, he made efforts to alleviate the misery of these colonies, which had no resources. He set up a civil registry, prompted Catholic missionaries to build a school for boys, and even planned a school for girls. He built roads, researched the possibility of digging a harbor, and developed the cultivation of coffee, indigo plants, mulberry trees, and nutmeg trees. He also organized defense against possible British assaults. In 1756, Bouvet asked to go back to France, but the inhabitants of Île de France begged him on their knees not to leave yet. In 1763, as the two islands returned to the control of the government after the cessation of the India Company, Bouvet remained in Bourbon, giving away his salary to cover supply expenses.

Bouvet went back to France in December 1763 and was awarded military nobility in 1774, being praised with the comment: "He may be the greatest and most capable seaman the Company has ever had in its service." Bouvet died in 1781 at his estate of Vauréal, near Paris.

Gracie Delépine

See also **Bouvetøya**

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BOUVETØYA

Bouvetøya (Bouvet Island) is located at 54°26′ S, 3°24′ E in the South Atlantic Ocean and is one of the most isolated islands in the world. Due to its steep coastline, it is also one of the most inaccessible, and 93% of the surface is covered by glaciers. The island is 9.5 km long and 7 km wide and covers an area of 49 km^2. The climate is oceanic with an annual mean temperature of –1°C. Bouvetøya is usually shrouded in clouds, but the crater rim and the highest point—780 m—may be seen on rare occasions.

Bouvetøya rises from the Mid-Atlantic Ridge as a volcanic cone. The oldest basalt rocks are 1.3 Ma, while the youngest lavas are 0.1 Ma. Fumaroles are abundant.

There are no grasses or flowering plants at Bouvetøya, but there are approximately seventy species of terrestrial cryptogamic plants: mosses, liverworts, lichens, and fungi. The flora are very similar to those of other Antarctic islands farther to the west. Regarding terrestrial animals, only four species of mites and three of springtails have been recorded. The most common species are the oribatid mite *Alaskozetes antarcticus* and the collembolan *Cryptopygus antarcticus*.

The southern elephant seal and the Antarctic fur seal breed on Bouvetøya. The population of elephant seals ranges from 200 to 400 individuals. Fur seals were heavily hunted by Norwegian whalers in 1927, but to prevent eradication, further hunting was stopped. About 1200 fur seals were counted in 1928.

There are several penguin rookeries at Bouvetøya, mainly made up of chinstrap and macaroni penguins. The latter type is the most numerous. Some of the rookeries are located in the steep mountain sides of the island. A small number of Adélie penguins are also breeding, as well as eight other species of seabirds.

Due to a landslide between 1955 and 1958, a new relatively flat area was formed at the western side of the island. The Westwindstranda is approximately 1500 m long and up to 300 m wide. The highest point, called Nyrøysa, rises 33 m above sea level. Westwindstranda was quickly colonized by penguins and seals. A Russian expedition counted approximately 950 penguins in 1958, but in 1979 Norwegian scientists found that the number had increased to almost 15,000. Later, the breeding grounds were taken over by fur seals, and the number of penguins had decreased to approximately 2000 in 2001.

The population of fur seals increased from 500 in 1964 to 66,000 in 2003.

Bouvetøya was discovered in 1739 by a French expedition headed by Jean-Baptiste Bouvet de Lozier. Due to unfavorable weather conditions, no landing was made, but Bouvet believed he had discovered the unknown austral continent. The island was revisited by British and American sealers in 1808 and 1822, and the first mapping was carried out by the German Valdivia expedition in 1898. In order to establish a whaling station, Bouvetøya was visited yearly by Norwegian expeditions on board the steamer Norvegia. Due to the steep topography, the station could not be built, but the island became a Norwegian possession in 1930. In 1971 it was proclaimed a Norwegian nature reserve, by which designation the ecosystems of the island and adjoining sea are protected.

LAURITZ SØMME

See also **Adélie Penguin; Antarctic Fur Seal; Bouvet de Lozier, Jean-Baptiste; Chinstrap Penguin; Christensen Antarctic Expeditions (1927–1937); Lichens; Liverworts; Macaroni Penguin; Mosses; Parasitic Insects: Mites and Ticks; Southern Elephant Seal; Springtails; Whaling, History of**

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BRANSFIELD STRAIT AND SOUTH SHETLAND ISLANDS, GEOLOGY OF

Bransfield Strait is situated at the southwestern end of the Scotia Arc, a large-scale tectonic structure linking South America and the Antarctic Peninsula. It is a young (<4 million years old) basin created when the South Shetland Islands crustal microplate migrated northwest, away from the northern Antarctic Peninsula. Rifting within the continental volcanic arc represented by the South Shetland Islands and northern Antarctic Peninsula caused the movement. The active rift is bounded by normal faults to the northwest and southeast and it extends about 400 km northeast from Low Island to Clarence Island where it is terminated by major oblique cross-faults. Seismic refraction studies have shown that the basin is formed in thinned continental crust on top of about 30 km of "anomalous" crustal material. The extension is probably a result of Drake Passage oceanic crust rolling back at the South Shetland trench. The oceanic crust is probably still being consumed (subducted) beneath the islands at a very slow rate. Three major sub-basins are informally defined. The south Bransfield basin extends between Low Island and Deception Island and is the shallowest, with depths typically <1000 m. The central Bransfield basin is up to 2 km deep, about 40 km wide, and 200 km long between Deception Island and Bridgeman Island. It includes the prominent 20- by 50-km, flat-floored King George basin, a sub-basin that is also the site of high heat-flow values and hydrothermal venting. Similar vents also occur buried in the Deception Island caldera. The north Bransfield basin is the deepest and structurally most complicated, with maximum depths over 2700 m.

The seafloor of Bransfield Strait is covered by very young sediments draped over a substrate of volcanic rocks formed during the rifting process. The latter form a series of seamounts and discontinuous ridges. Together, they comprise an incipient mid-ocean ridge, which, as is unusual for mid-ocean ridges generally, is exposed subaerially at Deception and Bridgeman islands. The volcanism in Bransfield Strait started at least 0.3 Ma and continues today at Deception Island. From compositional studies of volcanic ash preserved as layers in ice caps on the South Shetland Islands and in marine sediments, it is known that at least three different volcanoes erupted in Bransfield Strait during the past few thousand years (Deception Island, Bridgeman Island, and a third presumably submarine volcano whose location is currently unknown). Deception Island has been particularly active, with multiple eruptions during the last few tens of thousands of years. The volcanic ashes were dispersed up to 800 km across the Scotia Sea and, in one case at least, as far as the South Pole (3000 km away).

Because of the setting, the volcanic rocks show some of the chemical characteristics of the older continental volcanic arc magmatism as well as features of volcanoes in oceanic basins. Smaller volcanic edifices near the northeastern end of the basin are composed of basalts with the most arc-like compositions, whereas basalts with compositions most similar to mid-ocean ridges occur toward the southwest end. The latter include a large caldera-topped seamount and, unusually, some magmas with andesite and rhyolite compositions. Bridgeman Island contains basaltic andesites and Deception Island has a broad compositional series ranging from basalts to dacites. Low-pressure fractional crystallization of olivine, spinel, and plagioclase can account for most of the compositional variations within the individual volcanoes, whereas differences between volcanoes are probably a result of different mantle sources and melting processes. There are no clear systematic volcanic and chemical variations along the basin axis, suggesting no strong support for the model of unidirectional (southwest) propagation of rifting suggested by geophysical data.

For simplicity, the geology of the South Shetland Islands can be divided into two parts: the metamorphic rocks of the Elephant and Clarence Islands Group and Smith Island, and the mainly volcanic and sedimentary rocks that form the islands from Low Island to King George Island. The metamorphic rocks were pervasively recrystallized under a variety of conditions corresponding to greenschist, albite–epidote–amphibolite, and blueschist facies. The blueschists on Smith Island were the first rocks of their type to be discovered *in situ* in Antarctica, as recently as 1975, although similar rocks were also discovered later on Elephant Island. Their particular importance is due to the unusual conditions required for their formation, corresponding to high pressures (i.e., crustal depths of about 20 km) yet low temperatures (350°C). Rare relict detrital textures, pillow lavas, and cherts are also preserved on Elephant Island, and serpentine-altered ultramafic rocks on Gibbs Island. The distinctive combination of lithologies; low temperatures and high pressures required for the metamorphism; and deformation style have been attributed to formation within an accretionary prism during subduction at the South Shetland trench (i.e., material scraped off the downgoing oceanic plate and underplated on the leading edge of the overriding continent). The metamorphism and therefore subduction probably took place around 109–101 Ma (Elephant and Clarence Islands Group) and 47 Ma (Smith Island) but there is also some evidence for much older metamorphism (at 240–280 million years). The younger ages may represent overprinting by later deformational and metamorphic events.

The oldest rocks elsewhere in the South Shetland Islands are quartz-rich sandstones of the Triassic age that were deposited 240 Ma. Although the strata are exposed only on one peninsula on Livingston Island, similar rocks form extensive outcrops in the northern Antarctic Peninsula, suggesting a formerly much wider distribution, and they may underplate most of the islands. The sequence is predominantly overturned and it may form a very large overfold. Metamorphism is only weakly developed and the original sedimentary structures are well preserved. The sediments were deposited in submarine fans along a mature continental margin, but the tectonic setting of the formation is not well known, ranging from the shallow structural levels of an accretionary prism to a fore-arc basin.

Marine sedimentary rocks on Low Island were deposited in a sedimentary basin on the ocean side of an active volcanic arc during the late Jurassic (155 Ma), which was then situated in the northern Antarctic Peninsula. However, in the earliest Cretaceous times (at about 144 Ma), the South Shetland Islands became the location for the active arc that subsequently dominated the geological development of the island group. The oldest of these arc products are associated with fossiliferous marine and nonmarine sandstones and conglomerates of the early to mid-Cretaceous age (140–100 Ma) on western Livingston Island and Snow Island. The compositions of those volcanic rocks are mainly basaltic but they also include the only rhyolites known in the islands. The South Shetland volcanism migrated northeastward with time, so that the next youngest volcanic strata occur in eastern Livingston Island, where they comprise subaerially erupted basalt–andesite volcanics around Mount Bowles, and sedimentary strata at Williams Point and Moores Peak. The Williams Point Beds were eroded from volcanic terrain and deposited in late Cretaceous (90–80 Ma) riverbeds. They contain some of the best-preserved plant fossils from Antarctica. By contrast, the Moores Peak beds formed after a major collapse of one of the Cretaceous volcanoes.

Younger volcanic strata crop out in the central and eastern islands. They range in age from the latest Cretaceous (about 80 Ma) on Robert and Greenwich islands to Palaeocene–Eocene (60–40 Ma) on King George Island. Like the earlier volcanism, they were erupted subaerially and those on King George Island also contain former lake deposits with abundant very-well-preserved plant fossils. The activity continued to be dominantly basaltic, but very thick andesite lavas with spectacular columnar jointing are particularly common in the Eocene strata. Basaltic volcanism recommenced after a 10-million-year gap but it was now located in eastern King George Island, where basalt to dacite lavas were erupted. Although mainly subaerial, they included several small volcanoes erupted into seawater with very primitive compositions. These younger rocks are also associated with sedimentary deposits related to at least three glacial periods, called the Polonez (29–26 Ma), Melville (23–22 Ma), and Legru (age uncertain) glaciations. The Polonez Glaciation is the oldest glacial period represented onshore in Antarctica. Both the Polonez and the younger Melville glacial units contain abundant marine fossils. They also contain fragments of distinctive rock types that must have travelled at least 2000 km from the likeliest source areas in the Transantarctic and Ellsworth mountains in East Antarctica. Marine siltstones and sandstones less than 20 million years in age, which occur in the Seal Islands (off the north coast of Elephant Island), are the youngest sedimentary strata in the South Shetland Islands. They may also have formed during a cold-climate period, but their precise age and origins are not yet clear.

The volcanic activity seems to have died out at around 24 Ma, but it recommenced about 1 Ma when several small ash cones were erupted on northeastern Livingston and northern Greenwich islands. Penguin Island is also part of that phase of activity although it is lava dominated and separated from the other centres by over 100 km. The island also contains a well-preserved volcanic cone, which may have been active in the last few hundred years. The origin of this final phase of volcanic activity is probably related to the regional extension associated with the rifting of Bransfield Strait, and the young volcanic centres show a variety of compositions ranging from sodium-rich alkaline magmas to island arc magmas.

Plutonic intrusions, mainly granodiorite, are also present on many of the islands. They have a range of ages that mirrors the general trend of northeasterly-younging seen in the volcanic suites. The oldest intrusion is on Low Island (120 Ma) whilst the youngest occurs on Cornwallis Island (9.5 Ma) over 400 km to the northeast. The latter is the youngest granite intrusion dated so far in Antarctica.

J. L. Smellie

See also **Antarctic Peninsula, Geology of; Deception Island; Drake Passage, Opening of; Fossils, Plant; Geological Evolution and Structure of Antarctica; Glacial Geology; Islands of the Scotia Ridge, Geology of; King George Island; Plate Tectonics; South Shetland Islands**

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BRAZIL: ANTARCTIC PROGRAM

Scientific activities performed by Brazil in the Antarctic take place under the aegis of the Programa Antártico Brasileiro (PROANTAR, the Brazilian Antarctic Program). Implementation of PROANTAR is under the responsibility of the Comissão Interministerial para os Recursos do Mar (CIRM, the Interministerial Commission for Sea Resources), a federal multiministerial organization coordinated by the commander of the Brazilian Navy, Ministry of Defense (formerly Ministry of Navy). Its executive branch is the Secretaria da CIRM (SECIRM), coordinated by the Brazilian Navy.

PROANTAR was created in December 1982, 7 years after Brazil's adherence to the Antarctic Treaty (1975), when the first national scientific expedition was dispatched to the Antarctic region. A geographic survey of possible sites for installing a research station and scientific investigations in the fields of upper-atmosphere physics, biological oceanography, and meteorology took place during the summer aboard the oceanographic ships *Barão de Teffé* (Brazilian Navy) and *Prof. W. Besnard* (Universidade de São Paulo). Initiation of PROANTAR and scientific results obtained during the first Brazilian Antarctic expedition allowed Brazil to become a Consultative Party to the Antarctic Treaty in 1983 and Member of SCAR in 1984.

Until 1990, SECIRM was in charge of both conducting the Antarctic science program and supporting activities of PROANTAR. From 1991 on, the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq, National Council for Technological and Scientific Development), an agency of the Ministério da Ciência e Tecnologia (MCT, the Ministry of Science and Technology), was in charge of the scientific activities of PROANTAR. Other important components of the Brazilian Antarctic system are the Ministério das Relações Exteriores (MRE, Ministry of Foreign Relations), MCT, and Ministério do Meio Ambiente (MMA, Ministry of Environment). MRE, through its Comissão Nacional para Assuntos Antárticos (CONANTAR, National Commission for Antarctic Affairs) elaborates the Política Antártica Nacional (POLANTAR, National Antarctic Politics). The POLANTAR expresses the Brazilian national interests in the Antarctic region, the main objectives and lines of action of PROANTAR. MCT houses the Comitê Nacional de Pesquisas Antárticas (CONAPA, National Committee on Antarctic Research). CONAPA provides a link between the Brazilian Antarctic science community and the Antarctic science activities and initiatives internationally promoted and coordinated by SCAR. The MMA is responsible for the implementation of measures in the Protocol on Environmental Protection to the Antarctic Treaty with regard to Brazilian activities in the Antarctic. Scientific research within PROANTAR is performed in a decentralized way by a number of universities and research institutions (average twenty-five) from all over the country.

Supporting activities provided by SECIRM to PROANTAR include logistic operations, education in Antarctic matters (particularly with reference to environmental questions), and pre-Antarctic expedition training of scientists and supporting personnel. In association with the Fundação Universidade Federal de Rio Grande (FURG, Foundation Federal University of Rio Grande), SECIRM runs the Estação de Apoio Antártico (ESANTAR, Antarctic Supporting Station) in Rio Grande, southernmost Brazil. ESANTAR keeps and maintains Antarctic clothing, vehicles, camping gear, and other equipment utilized in annual Antarctic fieldwork. Since 1996, the oceanographic vessel *Ary Rongel* (Brazilian Navy) has been utilized for transporting PROANTAR participants and for resupplying Brazilian science facilities in Antarctica. Transportation of cargo and personnel is also provided by the Brazilian Air Force, which performs several flights year-round to the Chilean air strip at base Presidente Frei, on King George Island.

Brazilian Antarctic installations include the Estação Antártica Comandante Ferraz (EACF, Commander Ferraz Antarctic Station) and three summer refuges on Elephant Island, Nelson Island, and Fildes Peninsula, King George Island. Built in 1984 on Keller Peninsula, Admiralty Bay, King George Island, EACF became a year-round station in 1986. It can accommodate around forty-six persons in summer and twenty-two in winter.

Evaluation of projects submitted by the Brazilian scientific community to PROANTAR is made by CNPq through its Grupo de Assessoramento do PROANTAR (GA, Assessing Group) using a peer-review process, on the basis of scientific consistence, relevance to main Antarctic science questions, and quality of team. All projects are previously reviewed with regard to their possible environmental impact by the Grupo de Avaliação Ambiental (GAAm, the Environmental Evaluation Group of MCT). Approved projects are then examined for their logistical requirements by the Grupo de Operações (GO, Operations Group of SECIRM).

Prior to 2002, the scientific content of PROANTAR was made up of projects submitted by Brazilian researchers in the general fields of atmospheric sciences, life sciences, and Earth sciences, initially supported by SECIRM and later by CNPq. A major restructuring of PROANTAR scientific organization then took place as a combined initiative of MMA and CNPq. The reorganization involved the establishment of two nationwide research networks formed by numerous multidisciplinary and multi-institutional research groups with a focus on the investigation of Antarctic environmental changes.

Network 1 aims at analysing changes that may be occurring in the Antarctic Peninsula region, with regard to their possible interaction with terrestrial processes outside Antarctica, particularly those that might have an effect on the Brazilian territory. Network 2 intends to produce a detailed diagnosis of the present state of the Antarctic environment within the Antarctic Specially Managed Area Admiralty Bay, where a substantial part of the Brazilian Antarctic activities take place. Network 1 includes about sixty researchers from seven research groups. The number of scientists involved in Network 2 is around 120, representing 15 research groups. Around thirty Brazilian research institutions are presently active in PROANTAR. Scientists from sixteen international institutions collaborate with the two networks. Both networks are intended to be pluriannual activities with an initial duration of 3 years. A smaller percentage of the science budget is dedicated to supporting high-quality, innovative research projects proposed by scientists or science groups.

Scientific results of PROANTAR are published in both national and international peer-reviewed journals. Lists of publications appear annually in the Brazilian report to SCAR and may be examined in existing databases maintained by CNPq. Pesquisa Antártica Brasileira (Brazilian Antarctic Research), the PROANTAR scientific journal, is published by the Academia Brasileira de Ciências (Brazilian Academy of Sciences) on behalf of the program with the financial support of CNPq.

PROANTAR is a modestly funded Antarctic program with a total yearly budget of around 1.5 million US dollars (2001–2004). Of this amount, approximately 30% goes to science while 70% is spent on supporting activities. Research is presently funded by resources from both CNPq and MMA. Resources for supporting activities come from SECIRM.

ANTONIO C. ROCHA-CAMPOS

See also **Antarctic Peninsula; Antarctic Treaty System; King George Island; Protocol on Environmental Protection to the Antarctic Treaty; Scientific Committee on Antarctic Research (SCAR)**

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BRITISH ANTARCTIC (*EREBUS* AND *TERROR*) EXPEDITION (1839–1843)

On June 1, 1831, James Clark Ross located the North Magnetic Pole near Cape Adelaide on the west coast of Boothia Peninsula. Hence, when the Royal Navy was persuaded to mount an expedition to carry out a series of observations at fixed stations in the Southern Hemisphere and, if possible, to locate the South Magnetic Pole, the choice of Ross, by then a captain, to lead the expedition was a natural one.

The ships allocated to the expedition were two barque-rigged bomb-vessels, HMS *Erebus* and *Terror,* 372 and 326 tons respectively. Second in command (and captain of *Terror*) was Captain Francis Crozier, who had sailed with Ross on William Edward Parry's second, third, and fourth Arctic expeditions. Surgeon on board *Erebus* was Robert McCormick, who also filled the functions of geologist and ornithologist; assistant surgeon was Joseph Dalton Hooker, who also acted as botanist. The total complement of the expedition was 126 men.

The expedition sailed from Margate Roads on September 30, 1839. Having called at Madeira, the Canary Islands, Cape Verde Islands, St. Paul Rocks, and Trindade, on January 31, 1840 they reached St. Helena, where the first magnetic station was to be established. Army officer Lieutenant Lefroy and a party were put ashore, but it was soon discovered that the island was particularly unsuitable for magnetic studies due to great anomalies produced by its volcanic rocks.

The ships put to sea again on February 9, 1840, reaching Simon's Bay near Cape Town on March 16. Lieutenant Wilmot and a party went ashore to set up a magnetic observatory, and then, on April 6, the ships put to sea again, and were soon separated in bad weather. *Erebus* sailed close past the Prince Edward Islands and then, during the period April 25–30, charted the Crozet Islands (today known as Îles Crozet), some distance from where previously plotted.

Both ships reached Kerguelen on May 5. Ten days later, they were warped to the head of Christmas Harbour, where two observatories were built on the beach—one for magnetic studies, the other for astronomical observations and pendulum studies—as well as huts for the observers. Here the ships stayed for over two months marked by foul weather with gale-force winds, rain, and snow on most days.

Putting to sea again on July 20, the ships ran eastwards to Van Diemen's Land (Tasmania) and reached Hobart on August 16 and 17. Here Ross and his officers were given a very warm welcome by the Lieutenant Governor, Sir John Franklin, who helped choose a site for the observatories; 200 convicts were assigned to dig the foundations. Leaving Lieutenant Joseph Kay and two mates to continue the observations, *Erebus* and *Terror* sailed again on November 12, 1840, bound next for the Auckland Islands; here, in Port Ross, a further set of observatories was built, and the ships stayed for a month, while the usual magnetic observations were carried out and the harbour surveyed.

On December 12, the ships put to sea again, bound next for Campbell Island, where they spent a few days. They then headed south, in search of the South Magnetic Pole. The first iceberg was seen on December 27, and the edge of the pack ice was encountered on New Year's Day, 1841, right on the Antarctic Circle. The ships entered the pack ice on January 5 and, taking advantage of leads and polynyas, worked their way south. Adélie penguins provided great entertainment; numerous seals, mainly crabeater and Weddell seals, were seen; one that was shot proved to be of a new species: a Ross seal.

By January 8, a dark water-sky was visible to the south and by the following morning they had penetrated the belt of pack ice that guards the Ross Sea almost permanently, to reach the open waters beyond, the first ships ever to do so. On the morning of January 11, an imposing range of snow-covered mountains was sighted ahead, the Admiralty Range in Victoria Land. Measurements of dip and variation revealed that the Magnetic Pole must lie more than 500 miles (800 km) to the southwest, that is, well inland and hence inaccessible by sea.

The next morning, parties from both ships, led by their captains, landed on a small island that Ross named Possession Island; here he raised the Union Jack and claimed the new lands for Queen Victoria. The ceremony was held in the middle of a noisy, smelly penguin rookery.

Pushing southward Ross passed and named two islands, Coulman Island, named after the father of Ross' fiancée, Ann, and Franklin Island, on which a landing was made. On January 27, a conspicuous, snow-covered, conical peak appeared dead ahead. Next day it was revealed to be an active volcano, emitting dense clouds of smoke and gouts of flame. It was named Mount Erebus and an adjacent, extinct volcano Mount Terror.

The ships had just passed another small island, named Beaufort Island, when a continuous, low, white line extending along the horizon was spotted ahead. As they approached it became steadily higher, until it appeared to be a continuous ice-cliff, 165–200 feet (50–60 m) high, its top absolutely level and stretching out of sight to the east. Ross named it "the Barrier"; he had discovered the front of the Ross Ice Shelf, a vast expanse of floating glacier ice filling the southern part of the Ross Sea and produced by the convergence of a large number of outlet glaciers fed from the Antarctic Ice Sheet. Its front is about 500 miles (800 km) wide, and it extends almost 600 miles (965 km) from north to south, narrowing southwards. It thus covers about 180,000 square miles (466,000 km^2), about the same area as France.

Swinging east along the Barrier, Ross traced it for a distance of some 375 miles (600 km), but found no break in it, nor any diminution in height. Finally, blocked by pack ice, on February 12 Ross started back west. Passing Mount Terror and Mount Erebus again, Ross established that they were on an island (since named Ross Island), beyond which he discovered an embayment that was named McMurdo Bay (now McMurdo Sound) after Terror's first lieutenant. Ross had hoped to find a wintering site here, but the approaches were blocked by fast ice; coasting back north along the Victoria Land coast, he was unable to find a suitable wintering site there either, so on February 26 he started back north for Hobart, arriving there on April 7, 1841.

In Hobart the ships were refitted, while the crews relaxed. The ships departed again on July 7, 1841, and reached Sydney a week later. An observatory was established on Garden Island in Sydney Harbour, and there observations were made for comparison with simultaneous observations made at Hobart. The observations completed, the ships put to sea again on August 5, bound for Bay of Islands, New Zealand, where they remained for three months while the now-standard magnetic, pendulum, and meteorological observations were made.

Erebus and *Terror* sailed again on November 23, 1841, southward bound, once again, for the Ross Sea. The first pack ice was encountered on December 16, much farther north than in the previous year. Once again they crossed the Antarctic Circle on New Year's Day. On January 19, 1842, the ships were struck by a violent gale while they were in heavy pack ice and the rudders of both ships were smashed. After this damage was repaired, they finally reached the open waters of the Ross Sea again in the early hours of February 2. The Barrier again hove into view on February 22, and the two ships swung east to trace it for some 10° of longitude farther than they had the previous year.

With new ice starting to form, Ross now headed back north. Emerging from the pack ice on March 1, he swung east, bound for Cape Horn. But there were still large numbers of icebergs, and on the night of March 12–13, while trying to avoid a large berg that had loomed out of the darkness, the two ships collided and their rigging became entangled. Ross managed to extricate himself from this predicament by backing his sails, getting some sternway on his ship, then maneuvering her through the rapidly closing gap between two other very large bergs.

The damage repaired, the ships continued to run east, passing Cape Horn, and on April 6, 1842, reached Port Louis in the Falkland Islands, where they were to spend most of the winter. Observatories were set up and the usual schedule of magnetic, pendulum, astronomical, and meteorological observations began. Both ships, in turn, were emptied of stores and equipment and were careened on the beach so that the damage to their hulls could be repaired. Leaving an officer to continue the magnetic observations at Port Louis, on September 8, 1842, the ships sailed for Cape Horn, where Ross wanted to make comparative magnetic measurements. They reached St. Martin's Cove, Hermite Island (just north of Cape Horn), on September 20. An observatory was set up and the observations continued for a month. The ships then returned to the Falklands, arriving on November 13.

A month later, on December 17, the magnetic observations at Port Louis completed, Ross put to sea, heading south once again. He planned to investigate the western shores of the Weddell Sea. Arguing that prevailing westerlies should push the pack away from the western shores, he hope to attain a higher latitude than Weddell's record of 74°15′ S.

Passing east of Clarence Island, the two ships raised Joinville Island, off the northeastern tip of the Antarctic Peninsula. Manoeuvring in thick weather, on December 31 Ross was rewarded with a fine, clear day, which found him south of Dundee Island (which he mistook for part of Joinville Island) in the wide embayment of Erebus and Terror Gulf. On January 6, 1843, Ross, Crozier, and the other officers landed on Cockburn Island and took possession of all the islands visible. Running south and west past Seymour and Snow Hill islands, by mid-month the ships were brought up by the edge of the fast ice to the south. On February 1 Ross abandoned any hope of getting farther south in this area; he got clear of the ice by February 4 and headed east along the edge of the pack. The latter began to trend southeast and, following it, Ross not only crossed the Antarctic Circle for the third time, but reached 71°30′ S before being blocked by pack ice on March 5, 1843, off the coast of Queen Maud Land.

Extricating his ships from the ice, Ross next set a course for the Cape of Good Hope. *Erebus* and *Terror* dropped anchor in Simon's Bay on April 4. Having completed the magnetic observations there, they sailed again on April 30 and having called at St. Helena, Ascension, and Rio de Janeiro, they reached Folkestone on September 4. They were paid off at Woolwich on September 23.

James Clark Ross had exceeded by an enormous margin the original aims of his expedition. Having conducted magnetic observations for varying lengths of time at nine different observatories in the high southern latitudes, he had vastly expanded the knowledge of magnetism in the Southern Hemisphere. And from his measurements of dip and variation in the Ross Sea, he had proved incontrovertibly that the South Magnetic Pole lay some five hundred miles inland from that sea. But in addition to this, Ross was the first to penetrate the ice-free waters of the Ross Sea, the first to see Mount Erebus, and the first to see and map the Great Ice Barrier or Ross Ice Shelf.

Of the published scientific results of the expedition, the most voluminous were those analysing the results of the magnetic observations, published during the period from 1843–1868, and the analysis of Hooker's botanical collections. His beautifully illustrated Flora Antarctica, a groundbreaking work, was published in two volumes. The expedition also made useful contributions in the areas of oceanography and marine biology. As the first multidisciplinary Antarctic expedition, it set a very high standard for all those that followed.

William Barr

See also **Campbell Islands; Crozet Islands (Îles Crozet); Hooker, Joseph Dalton; Kerguelen Islands (Îles Kerguelen); Prince Edward Islands; Ross Ice Shelf; Ross Island; Ross, James Clark; Ross Seal; South Pole; Victoria Land, Geology of**

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BRITISH ANTARCTIC *(NIMROD)* EXPEDITION (1907–1909)

Although attaining the North Pole had been the aim of many expeditions in previous decades, the British Antarctic Expedition of 1907 was the first to have the explicit goal of reaching the South Pole, which remained one of the last great mysteries on Earth. One should not be confused by the expedition's grand title, however; it was not a national effort, but very much the brainchild of one man—Ernest Shackleton.

Shackleton's desire to lead such an expedition came from his experiences on the British National Antarctic Expedition (1901–1904) under Robert Falcon Scott, on which he had served as third officer.

In the summer of 1902–1903, Scott, Shackleton, and surgeon Edward Wilson attained a farthest south of 82°17′ S on the Great Ice Barrier (now known as the Ross Ice Shelf). During the journey, all three suffered from scurvy, with Shackleton by far the most severely affected, which led to Scott invaliding him home against his will. Shackleton's desire to prove that he should not have been sent back early—as well as his belief that a successful attempt on the Pole could gain him fame and fortune—led him to consider commanding his own expedition, although he received little encouragement for several years.

In February 1907, a bank loan of £7000 was guaranteed for Shackleton by his employer, the Scottish industrialist William Beardmore. This allowed the explorer to move forward with his plans, which included leaving England that very year. Shackleton soon found that Scott also hoped to return to the Antarctic, and that his former commander did not want him using their previous base at Hut Point on Ross Island, nor even going near Ross Island or its adjacent McMurdo Sound. After extensive negotiations, Shackleton agreed to land instead at King Edward VII Land. This was a major concession because Ross Island abutted the Barrier and appeared, at that point, to be the start of the ideal road to the pole, whereas no one had ever landed at King Edward VII Land, hundreds of miles away from McMurdo Sound at the eastern edge of the Great Ice Barrier. While conditions to the south of it were totally unknown, it was the only other place that seemed within striking distance of the pole.

Key to Shackleton's hopes for reaching the pole were two forms of transport never before used in the Antarctic: an Arrol-Johnston motor-car given him by Beardmore (who owned the company) and Manchurian ponies. Shackleton was convinced to take ponies by Frederick Jackson, who had used them in his exploration of the Arctic archipelago of Franz Josef Land. The lack of success with dogs on Scott's expedition—caused in great part by inexperience with the animals—had left him and his former companions with little trust in them, so, although he brought a handful of dogs south, Shackleton planned to manhaul should the motor-car and ponies fail.

On August 7, 1907, the expedition ship Nimrod—a former Newfoundland sealer—departed from England, having been visited at Cowes 3 days before by King Edward VII and the Royal family. While the ship proceeded slowly to New Zealand, Shackleton remained behind to continue raising funds, major contributions already having been made by William Bell, Campbell McKellar, and the Earl of Iveagh. Significant funding also was contributed by the family of Sir Philip Brocklehurst, the 20-year-old baronet becoming the first subscribing member of an Antarctic expedition.

In December, while travelling to Lyttelton, New Zealand, to join the ship, Shackleton met with Professor Tannatt William Edgeworth David, a renowned geologist at the University of Sydney. Shackleton and David had agreed that "The Prof," as he came to be known, would accompany the expedition to Antarctica and then return north on *Nimrod,* which would winter in New Zealand, while the expedition staff remained in the Antarctic. Politically influential, David helped convince the Australian government to grant the expedition £5000, which allowed Shackleton to add one of David's former students—Douglas Mawson, a geologist at the University of Adelaide—to the shore party.

On January 1, 1908, *Nimrod* departed south, her lack of storage for coal requiring that she be towed some 1400 nautical miles (approximately 1600 statute miles or 2600 km) to the ice edge by the steel steamer Koonya. The difficulties of this effort were increased dramatically by a terrible storm that lasted for 10 days. Near the Antarctic Circle, *Nimrod* was cut loose, and moved south.

On January 23, the expedition approached the Great Ice Barrier. It soon became apparent that large sections had calved off since Scott's party had last visited the area. A new feature, which Shackleton named the Bay of Whales, had formed, and the entire episode led him to decide that setting up base on the barrier would be unsafe. They attempted to reach King Edward VII Land, but the tiny ship could not force her way through the heavy ice. After consulting with several of the shore party and Rupert England, the ship's captain, Shackleton decided the only viable way to protect his men and to keep faith with those funding and supporting the expedition was to break his promise to Scott and proceed to McMurdo Sound.

Miles of ice blocked the approach to Hut Point, however, and on February 3, Shackleton selected Cape Royds, a rocky promontory 18 miles (29 km) north on Ross Island, as his base. Here a hut was built for the fifteen men who would winter in the Antarctic, including David, who had decided to remain with the expedition and had designed for it a serious scientific program.

Unfortunately, the ice in McMurdo Sound broke up shortly after Cape Royds was occupied and *Nimrod* returned north, the open water and impassable conditions on the island itself cutting the shore party off from the road to the south until the sea froze over again the next winter.

In order to keep his men occupied and their spirits high, Shackleton decided they should make the first ascent of Mount Erebus, the active volcano on Ross Island. On March 5, a party of six left for the attempt. David, Mawson, and assistant surgeon Alastair Forbes Mackay formed the intended summit party, and expedition second-in-command Jameson Adams, surgeon Eric Marshall, and Brocklehurst comprised the support party. Adams later decided that the entire party would continue to the top. On March 10, having left Brocklehurst in his sleeping bag with frostbitten feet, the other five men reached the summit of the active crater, where they took photographs and made measurements before returning to the base.

In August, after the sea had again frozen over and the worst of the winter was past, Shackleton began sending parties south, in order to move supplies to Hut Point and to give sledging experience to his men, only two of whom—Frank Wild and Ernest Joyce—had previous Antarctic experience. Shackleton's plan entailed breaking his party into four groups, one of which would remain at Cape Royds and carry out scientific studies. Two of the other groups would make attempts on the South Pole and the South Magnetic Pole, respectively, while the third would engage in a geological field trip to the mountains west of McMurdo Sound.

Shackleton's plans for the Southern Party had been revised after they found that although they could use the motor car to positive effect on smooth sea ice; it was not suitable for the snow-covered barrier. More importantly, of the ten ponies brought south, only four were still alive: two had been put down aboard ship due to injuries, and four had died at Cape Royds due to eating corrosive materials or salt-covered sand. With only four ponies, the Southern Party was cut from six to four men. Accompanying Shackleton were Wild, Marshall, and Adams.

On October 29 the polar party headed south, each leading a pony. A five-man support group carried extra supplies before turning back on November 7. Early on, Shackleton cut the carefully planned rations, in order to extend the time away from base from 91 days to 110. The ponies quickly proved to be at a serious disadvantage in a glacial environment, needing to be protected from the cold and wind each night much more than dogs would have, and their sharp hooves and heavy bodies causing them to break through the coverings over crevasses more frequently than the men. On November 21 one of them had become so weak and inefficient he was shot. On November 26, in the middle of the barrier, they surpassed Scott's farthest south.

Two days later a second pony was put down, and on December 1 a third. Three men now hauled one sledge while Wild guided Socks, the last pony. Meanwhile, the line of the Transantarctic Mountains, which had previously paralleled their course, now curved to the east, blocking the explorers' path. In order to continue directly south and to avoid an area of the barrier that became violently disturbed with massive pressure ridges and increasing crevasses, the four men began to ascend what they called the Great Glacier (later named the Beardmore Glacier), which they hoped would take them through the mountains. On December 7, Socks fell down a crevasse, leaving them to proceed on their own.

For 3 weeks they struggled up the glacier, eventually reaching the Plateau, across which they continued, despite suffering from inadequate nutrition, high-altitude problems, extremely low temperatures, strong headwinds, and difficult sledging surfaces. By early January 1909 they realized that it was unlikely they would be able to attain the pole and return alive, but they were determined to reach within 100 miles of it. On January 9, after being kept in their tent for 2 days by a blizzard, they made a final push to 88°23′ S, only 97 geographic miles (112 statute miles or 180 km) from the pole. There Shackleton made one of his bravest decisions: turning back despite being so close to their goal. This decision allowed him to bring back all of his men alive.

The return north saw the four men repeatedly run out of food and just reach the supplies at the next depot. At one point travel was precluded altogether when all four suffered severe enteritis from eating pony meat that had gone bad. Hurrying desperately, because they were not certain if *Nimrod,* which was scheduled to return to the Antarctic from New Zealand, would wait for them beyond the end of February, Shackleton and Wild managed to reach Hut Point the night of February 28. They were picked up by the ship the next morning, and then returned to the barrier to collect Adams and Marshall, the latter of whom had collapsed.

Meanwhile, the Northern Party—consisting of David, Mawson, and Mackay—had left Cape Royds on October 5, 1908, to man-haul up the coast of Victoria Land until they could find a place to turn inland toward the South Magnetic Pole. Forced to relay their sledges because they had too many supplies to pull at one time, they made slow progress. In early November they passed over the Nordenskjöld Ice Barrier, and on December 1 they reached the massive Drygalski Ice Tongue, which took 10 days to cross. They began their ascent up a series of glaciers towards the Antarctic Plateau on December 16. Their trek inland continued for weeks, culminating on January 16, 1909, when, at 72°15′ S, 155°16′ E, they calculated they had reached the South Magnetic Pole. They then retraced their steps until blundering into a terribly crevassed and dangerous area near the base of the Larsen Glacier. They reached the coast in early February and were picked up by *Nimrod,* which had returned from New Zealand. They were almost left behind, because during a blizzard *Nimrod* passed where they were waiting, but the first mate, John King Davis, convinced the captain to go back—rather than abandoning the explorers to their fate as he intended—and they found the three men precisely where Davis had thought they might be.

Not long before, Nimrod had rescued the three members of the Western Party—Brocklehurst, Raymond Priestley, and Bertram Armytage. These three had formed part of the Southern Party's support before turning back. In December, they ascended the Ferrar Glacier, discovering defects in the maps prepared by Scott's expedition, and studying the geology of the area before returning to the coast to await the Northern Party. They were almost killed when the sea ice they were camping out on broke loose and started floating out of McMurdo Sound, but they managed to escape when it briefly brushed against the shore. After waiting for more than three weeks, they were finally picked up on January 24.

With all members safely on board, the expedition returned to New Zealand to great acclaim. While Shackleton and the members of the shore party were showered with honors, Davis, who had served as first mate throughout the expedition, successfully completed his first command by taking *Nimrod* back to England. On this voyage, Davis, who would go on to become the most experienced of all ship captains involved in Antarctic exploration, followed a far southerly route, which allowed him to prove that four sets of islands previously reported did not, in fact, exist.

The British Antarctic Expedition was very successful from both geographical and scientific standpoints. Shackleton and his companions recorded the greatest advance towards either end of the earth ever made, including beating the old farthest south record by 366 geographical miles. By pioneering the way to the central Antarctic Plateau, they proved beyond doubt the continental nature of Antarctica. They not only were the first to attain and record the nature of the far reaches of the barrier, as well as the Beardmore Glacier and the central plateau, but in doing so they opened the road that Scott would follow on his subsequent expedition.

Although the scientific contributions of David, Mawson, Priestley, and James Murray have been somewhat obscured due to those of Scott's expeditions and because of Shackleton's relative lack of interest in academic matters, large quantities of data were obtained at Cape Royds, on the ascent of Mount Erebus, the trek to the Magnetic Pole, and the Southern Party's journey. The geological surveys and studies carried out by David, Mawson, and Priestley extended and corrected the work from earlier expeditions, and the monograph on the geology of southern Victoria Land by David and Priestley remained the authoritative account for many years. Mawson also made the first serious study of the physical structure of Antarctic ice, and Murray the initial significant examinations of Antarctic freshwater biology in the lakes dotting Cape Royds.

Perhaps most importantly, the expedition introduced to the far south three men—David, Mawson, and Priestley—who would be giants in the history of Antarctic science, with Mawson leading the Australasian Antarctic Expeditions (1911–1914) and the British, Australian, New Zealand Antarctic Expedition (1929–1931). In the ensuing decades, David, Mawson, and Priestley all held major academic and administrative posts, through them serving as powerful advocates for Antarctic science, and helping establish, promote, and guide Antarctic research.

BEAU RIFFENBURGH

See also **Australasian Antarctic Expedition (1911–1914); British National Antarctic *(Discovery)* Expedition (1901–1904); David, T. W. Edgeworth; Davis, John King; Dogs and Sledging; History of Antarctic Science; Mawson, Douglas; Ponies and Mules; Priestley, Raymond; Ross Ice Shelf; Ross Island; Scott, Robert Falcon; Shackleton, Ernest; South Pole; Wild, Frank; Wilson, Edward**

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BRITISH ANTARCTIC *(SOUTHERN CROSS)* EXPEDITION (1898–1900)

In the last years of the nineteenth century, with individuals in Germany, Great Britain, and France trying to launch major national expeditions, a young interloper who was not part of the official geographical establishment persuaded a newspaper magnate, Sir George Newnes, to fund an expedition to Antarctica. The organizer, Carsten E. Borchgrevink (1864–1934), began his expedition amid a hostile environment in Great Britain led by the president of the Royal Geographical Society, Sir Clements R. Markham, whose vitriolic accusations against Borchgrevink must be understood in the context of an old man outdone by a younger and less experienced one.

Despite obvious shortcomings as a leader, Borchgrevink chose his staff wisely and produced a well-equipped expedition. The *Southern Cross* expedition sailed from London on August 28, 1898 and arrived in Tasmania in November 1898. From there, the men proceeded to Cape Adare at the northern tip of Victoria Land, a place Borchgrevink knew from a previous trip. The journey through the ice was arduous, and Captain Bernhard Jenson showed great skill in guiding his small craft through the dangerous water.

The length of time required for passing through the ice pack and the lateness of the season prevented extensive exploration by ship for other sites. The choice of Cape Adare proved to be an unfortunate one, as it did not allow easy access to other nearby areas. As a result, geographical discovery on land was limited, although the cruise during both the first and second summer afforded opportunities for geographical discovery. Still, the scientists, including Louis Bernacchi (1876–1942), Nicholai Hansen (1870–1899), and William Colbeck (1871–1930), made good use of their opportunity and produced a significant body of scientific research. *Southern Cross* departed Cape Adare to winter in Australia.

As a leader, Borchgrevink soon demonstrated his shortcomings, which were many. His lack of scientific expertise need not have been the severe disadvantage that he made it, but his overblown sense of his own scientific abilities provoked in his young scientific staff an early contempt that grew to dislike and then to hatred. Borchgrevink lacked appropriate humility and suffered, as many incompetents do, from an inability to recognize generously the quality of the work of others. Despite this, the scientists accomplished more than a year of magnetic and meteorological observations plus data on the local flora and fauna.

Borchgrevink's skills in choosing good equipment and, particularly, palatable and adequate food, meant that the health of his men remained good through the winter. An exception was Nicholai Hansen, who appears to have had preexisting health problems for which the expedition physician, Herlof Klovstad (1868–1900), was unable to find a cure. Hansen's death in October 1899 was the darkest moment in the expedition.

The wintering party lived in a prefabricated hut that, while small, was comfortable. They soon settled into a routine of scientific work. Borchgrevink's restless nature, combined with an ever-growing animosity from his staff, prompted him to make several winter sledging trips, often in the company of the two Sami that the leader had selected for the staff. These two men showed great acumen and were successful hunters.

The conditions of life together were not made easier by Borchgrevink's uneven temper and immoderate leadership. On several occasions he quarreled with his staff—even dismissing Colbeck from the expedition at one point. Still, the scientists persevered and Borchgrevink's lack of scientific leadership did not diminish the work of the expedition.

In January 1900, *Southern Cross* returned to Cape Adare, took on the wintering party, and then sailed south along the coast. The crew was as dazzled by the Ross Ice Shelf (then known as the Great Ice Barrier) as James Clark Ross' men had been 60 years earlier. Cruising along this huge wall, Borchgrevink's party came to an indentation in the ice shelf, an area subsequently known as Balloon Bight on the *Discovery* expedition. The ship established a new farthest south for a vessel, and two parties sledged out on the ice shelf. One, led by Borchgrevink, established a new farthest south. Again, as with his claim to the first on the last continent, the accomplishment had less actual import, but did give Borchgrevink a place in the annals of polar history.

The ship returned via Hobart to London in the summer of 1900. By that time, preparations for Robert Falcon Scott's British National Antarctic Expedition were well advanced, and Borchgrevink's estrangement from official geographical circles diminished the initial credit that his expedition received.

Aside from the scientific achievements, the *Southern Cross* expedition demonstrated that humans could winter on the Antarctic continent. Moreover, although subsequent expeditions did not always profit from the experience, this endeavor demonstrated the value of kayaks, skiing, and dogs as means of transport in the south polar regions and indicated that the Sami of the north could apply their polar survival expertise in Antarctica. That these lessons were not applied in subsequent Heroic Age expeditions, particularly other British ones, was less the fault of

Borchgrevink than of those in official geographical circles, who disdained learning from an outsider.

The *Southern Cross* expedition was a credible pioneering effort, successful in meeting many of its goals, and, as such, compares favorably with several other later British expeditions to 1922.

T. H. Baughman

See also **Borchgrevink, Carsten E.; British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); Markham, Clements; Ross Ice Shelf; Royal Geographical Society and Antarctic Exploration**

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BRITISH ANTARCTIC SURVEY

The origins of the British Antarctic Survey lie in World War II as a secret Royal Naval operation known as Operation Tabarin, established to counter the potential dangers from German commerce raiders in the Southern Ocean. There was also the political context provided by the conflicting territorial claims of the UK, Argentina, and Chile to Antarctic territory.

In February 1942, Argentina had reaffirmed its claim to the sector between 25° and 68°34′ W via an expedition to Deception Island and as far south as the Argentine Islands. This sector overlapped with the British claim (published in Letters Patent in 1908) from 20° to 80° W and known as the Falkland Islands Dependencies (FID). The first step in the British response was to send HMS *Carnarvon Castle* to Deception Island and Signy Island in January 1943 to reassert the British claim. Meanwhile on 28 January 1943 the British War Cabinet approved an expedition to the FID to strengthen the British title and deny the use of harbours and stocks of oil to enemy shipping. A small military force was tasked with establishing a wintering presence on the Antarctic Peninsula under the direction of the Royal Navy, but acting on behalf of the British Colonial Office. The code name "Tabarin" came from a Parisian nightclub well known to the organisers before the war.

Fourteen volunteers were selected in great secrecy, with the only clue as to their destination being the issue of sunglasses! They mustered at Port Stanley in the Falkland Islands and set off south on 29 January 1944 in two small ships, HMS *William Scoresby* and SS *Fitzroy*. The plan was to establish wintering stations on Deception Island and in Hope Bay on Trinity Peninsula. At Deception Island the base was established in Whalers Bay. Ice conditions meant that the ships could not safely land the people and equipment in Hope Bay, so they headed south down the western coast of the Peninsula, finally choosing Port Lockroy on Wienke Island as the site for the second station.

Tabarin had an advisory committee to provide polar expertise, consisting of James Wordie, a veteran of Shackleton's Imperial Trans-Antarctic Expedition; Dr. Brian Roberts, biologist on the 1935–1937 British Graham Land Expedition; and Dr. Neil Mackintosh, Director of the Discovery Investigations. Given this membership it was natural that the opportunity for doing science under the umbrella of a military operation was recognised and seized upon from the outset.

With the end of the Second World War, administrative control of the stations was transferred to the Colonial Office in recognition of the political purpose for which they were maintained. In July 1945, the operation was renamed the Falkland Islands Dependencies Survey (quickly shortened to FIDS). Whilst FIDS primarily operated to maintain a presence to support the British territorial claim, the work on the ground was predominantly expeditionary and scientific, with programmes of geology, biology, meteorology, survey, and mapping. In 1948, the Falkland Islands Dependencies Scientific Committee was appointed to report on scientific matters to the Colonial Secretary, whilst responsibility for the administration and operation of FIDS was formally transferred to the Governor of the Falkland Islands and Dependencies. The Governor established a small team in Port Stanley to manage the operation. At the same time, "Rear Base" was set up to provide the operational head of FIDS (SECFIDS) with an office when in London. Two years later the Falkland Islands Dependencies Scientific Bureau was established in London to coordinate the exploitation of the scientific data and samples collected by FIDS, with Dr. Vivian (later Sir Vivian) Fuchs as Principal Scientific Officer.

Over the next few years the many strands of management and oversight (Colonial Office, Governor FI, SECFIDS, Bureau and Rear Base) evolved so that in 1953 the Scientific Bureau became an integral part of FIDS, with Fuchs designated as Director of FIDS Scientific Bureau, responsible to the Governor. The first 5-year scientific plan was produced by the Bureau in 1955—starting a pattern of research management that continues today. Through the latter half of the 1950s there was much discussion about consolidation and reorganisation, so that finally in 1959 it was agreed that FIDS would be run as a single organisation with a director answerable to the governor. Dr. Fuchs was confirmed as director.

FIDS marine capability greatly improved at this time with the purchase of a Norwegian vessel, the MV *Arendal* (renamed the Royal Research Ship [RRS] *Shackleton*), in 1955, and the delivery of the new purpose-built RRS *John Biscoe* (the second FIDS vessel to carry this name) in 1956.

Around this time the spectacular success of the International Geophysical Year had resulted in the negotiation of the Antarctic Treaty, which came into force in 1962. One consequence was the redesignation of the British territorial claim to be the British Antarctic Territory, and following from that the renaming of FIDS as the British Antarctic Survey (BAS) on 1 January 1962. But the old acronym did not die; it just transmogrified to become the colloquial name for successive generations of field staff collectively known as Fids (standing for foolish idiots down south—or words to that effect!). With the renaming, London Office became the headquarters of BAS.

Over the next few years Sir Vivian Fuchs attempted to assure the long-term future of BAS within the UK government administration. Things came to a head in 1965 when the Treasury moved to have BAS wound up. The consequent review committee decided that BAS should continue, but become a component body of the recently formed Natural Environment Research Council (NERC). Thus on 1 April 1967 BAS transferred from the Colonial Office (and Governor FI) to NERC with a dowry of £1 million. This amounted to about 14% of the Council's budget, roughly the same as today.

During the early years, BAS relied upon a combination of *Biscoe, Shackleton,* and chartered vessels. But 1970 saw the delivery of a new much larger purpose-built logistics vessel, RRS *Bransfield.* This vessel, together with RRS *John Biscoe,* allowed BAS to dispense with ship charter.

Though BAS was now a single scientific organisation, the scientific staff were scattered around the United Kingdom and hosted in a variety of university departments, government laboratories, and museums. The HQ occupied a small office in London with a much larger logistics and administrative operations in Port Stanley.

In June 1967, a NERC Antarctic Committee was established to provide oversight of the BAS programme. In 1970, an additional committee was established by NERC—the BAS Advisory Committee—to provide the BAS director with advice on scientific matters. The question of whether BAS should be centralised at a single site was first raised in 1970, approved by NERC in June 1972, and finally realised at its present site in Cambridge in May 1976.

Sir Vivian Fuchs retired as director in 1973, to be succeeded by Dr. Richard Laws. This marked a watershed for BAS. Sir Vivian had successfully assured BAS's future in its permanent home, but during his tenure BAS had maintained an expeditionary ethos. Dick Laws began the process of building the organisation up as an integrated multidisciplinary research institute. However, he had to struggle continually against threats to reduce the budget. Soon after he took office BAS was required by NERC to cut expenditures by around 10%. NERC proposed that Halley Station be closed and *Biscoe* sold to save funds. These suggestions were countered successfully, but the consolidation of BAS in Cambridge offered an opportunity to save through a phased close-down of Stanley Office. By 1978, BAS representation in the Falklands was reduced to just one person, Myriam Booth, who continued in that role until her retirement in 2004. Also, increased use of snowmobiles and greatly improved air support through the acquisition of two DHC-6 Twin Otters allowed geological fieldwork without requiring science personnel to winter. This in turn allowed Stonington to be closed in February 1975.

Further budgetary pressure appeared in 1979, which caused BAS to look at several options for saving money, before deciding the least bad one was to close its station at King Edward Point on South Georgia. The Foreign and Commonwealth Office (FCO) was unhappy with this because BAS staff provided the administrative presence in the territory. They therefore agreed to fund the construction and operation of a new facility at King Edward Point. This was completed and ready for occupation at the end of March 1982.

The year 1982 was fateful for BAS, but it ultimately turned out to be the start of a new golden era. The new King Edward Point facility had only been occupied for 3 days before the Argentine invasion on 3 April saw the BAS team deported from there and interned briefly in Argentina before repatriation to the UK. The main invasion of the Falkands on 2 April had severed all communications between Cambridge and the Antarctic stations as this was routed via the cable and wireless radio station in Port Stanley. Other nations quickly came to BAS's aid by providing relays, and the BAS ships headed home maintaining radio silence and staying well away from South American ports.

The successful recovery of South Georgia and the Falkands by June 1982 had an enormous impact on BAS. The Prime Minister, Margaret Thatcher, decided that it was in the UK's interest to be a major player on the geopolitical stage where South Atlantic and Antarctic matters were concerned, and that one of the routes to achieving this would be via science. She directed that the BAS operating budget be doubled and a major capital investment programme be carried out. The realisation of this directive dominated the rest of the 1980s and early 1990s for BAS. The expansion was not always a smooth process; there were interdepartmental difficulties that sometimes delayed it, and also organisational problems. But by the early 1990s, BAS had been transformed into a highly capable and professional operation second to none in the world. Major investment provided an outstanding new research vessel—RRS *James Clark Ross*—to replace *Biscoe,* a new sophisticated station at Halley, redevelopment at Rothera to provide a crushed rock runway and wharf, a four-engined DHC-7 aircraft that provided an intercontinental capability to Rothera, and a fleet of four DHC-6 Twin Otters. In addition, all ships and stations were now communicating via digital geo-stationery satellite systems and all were provided with local area networks. Finally, there was redevelopment of the BAS Cambridge site that more than doubled the accommodations and provided world-class laboratory facilities.

The 1980s saw a scientific result come out of BAS that has assured both BAS and the three authors of the paper of their place in posterity. This was the discovery by Farman, Gardiner, and Shanklin of the ozone hole over Antarctica. That single result probably justifies all the money that the UK ever spent on Antarctic research, because of the paradigm shift that it caused, not just amongst scientists and politicians, but in the awareness it gave to the person in the street of our potential as a species to wreck our environment.

Further financial difficulties were encountered in the mid-1990s because the cost of operating and maintaining the new infrastructure was greater than anticipated. This led to a comprehensive internal review of scientific aims and consequent logistics needs. As a result, Faraday station was deemed surplus to requirement and was offered to and accepted by the Republic of Ukraine, who now operate it year round. Signy Island was reduced to a small summer-only facility and the main focus for inshore biology research was moved to Rothera, where a new sophisticated laboratory facility was built—the Bonner Laboratory. In 1999, *Bransfield* was finally retired from service to be replaced by a Norwegian vessel, acquired through a Private Finance Initiative deal and renamed the RRS *Ernest Shackleton*.

Dick Laws retired in 1987, to be replaced by Dr. David Drewry, who was director until 1994, followed by Dr. Barry Heywood, and then since 1998 by Professor Chris Rapley. These individuals have had to lead BAS through a tumultuous time. The relationship between BAS and NERC has at times been quite strained, stemming primarily from the fact that after the Falklands conflict the two separate strands to the BAS mission (political presence and basic science) were more starkly defined. The new funds were "ring-fenced" so that NERC, whilst accountable, was not in control, while the FCO took a strong interest in the political element of the mission. It is only in recent years that an effective relationship has developed. This has depended on a change of view in the UK in which government now recognises its research institutes as assets to be exploited and developed, and through a very determined push by BAS to ensure that its science portfolio is consistently world class, and to demonstrate this through rigorous peer review.

From a bunch of gifted amateurs doing a bit of science on the side whilst fighting a war, BAS has developed over the past 60 years into one of the UK's premier research institutes with a world-wide reputation for excellence.

JOHN R. DUDENEY

See also **Antarctic Peninsula; Antarctic Treaty System; British Graham Land Expedition (1934–1937); Deception Island; Discovery Investigations (1925–1951); Fuchs, Vivian; Geopolitics of the Antarctic; Imperial Trans-Antarctic Expedition (1914–1917); International Geophysical Year; Ozone and the Polar Stratosphere; South Georgia; Ukraine: Antarctic Program**

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BRITISH ANTARCTIC *(TERRA NOVA)* EXPEDITION (1910–1913)

On June 15, 1910, Captain Robert Falcon Scott's expedition ship, *Terra Nova,* set sail from Cardiff, Wales, bound for Antarctica. So began one of the most momentous and dramatic of all the expeditions of the Heroic Age of polar exploration. Scott had two principal ambitions: to be the first explorer to reach the South Pole, consequently surpassing the "farthest south" reached by Ernest Shackleton on the British

Antarctic Expedition on January 9, 1909, and to collect scientific data on the biology, geology, meteorology, and geophysics of Antarctica.

When *Terra Nova* reached Melbourne, Australia, Captain Scott was astonished to receive a telegram from the Norwegian polar explorer Roald Amundsen, indicating that he had turned from his professed attempt to reach the North Pole and was now proceeding for Antarctica. Scott realised that the "race for the South Pole was now on," and that he was no longer just in a contest with a former colleague and fellow Briton, but also with a very experienced polar explorer and representative of another country. He saw that the reputation of the British Empire was at stake.

Scott had joined the ship in Simon's Town, South Africa, and was enlisting further personnel in Melbourne and in New Zealand. *Terra Nova* was a converted Dundee steam-whaler of 700 tonnes gross that had been thoroughly overhauled and refurbished in the London docks on the Thames. The vessel was already heavily laden; in addition to large quantities of coal, there was a prefabricated hut, and all the provisions for a three-year stay in Antarctica. The ship carried sledges, thirty-four dogs, three motor sledges, an observation balloon, and a range of scientific equipment. Scott had selected a ship's complement of sixty-five, the ship's officers and crew seconded mainly from the Royal Navy, and the scientific staff from both the armed forces and academic life. Scott was in overall charge, and his second-in-command Lieutenant E. R. G. R. "Teddy" Evans, at that stage the ship's captain. The other officers included Lieutenant Victor Campbell; Lieutenant Henry Robertson "Birdie" Bowers; Captain Lawrence E. G. Oates of the Inniskillig Dragoons, who had general charge of the ponies; and naval surgeons G. Murray Levick and Edward L. Atkinson. The scientific staff was led by Scott's great friend from the British National Antarctic Expedition (1901–1904) Dr. Edward Wilson, and also included George Simpson, meteorologist; Frank Debenham, Raymond Priestley, and Griffith Taylor, geologists; Denis Lillie and Edward Nelson, biologists; and Charles S. Wright, physicist. Oates (nicknamed "Titus") and Apsley Cherry-Garrard had each paid £1000 to accompany Scott; "Cherry" was appointed assistant zoologist. Only Wilson and four petty officers—Tom Crean, Edgar Evans, William Lashly, and Thomas Williamson—had been before with Scott on *Discovery* on the earlier expedition, and Teddy Evans had assisted in the relief expedition to free *Discovery* from the ice.

In New Zealand the expedition was met by Scott's wife, Kathleen, and by Oriana Wilson and Hilda Evans, who had travelled out by passenger liner. A frenzy of activity of further "getting ready" took place, and the expedition was joined by Herbert Ponting, photographer; Lieutenant Wilfred Bruce, Scott's brother-in-law; Cecil Meares, dog handler, as well as the Russian dog-driver Demetri Gerov; and by nineteen Manchurian ponies and their Russian groom, Anton Omelchenko.

Terra Nova left Port Chalmers on November 29, 1910, and almost immediately encountered the first of many trials: a force-10 gale, which threatened to capsize the overladen vessel. The ship plunged and rolled in mountainous seas, shipping much water. Ten tons of coal were thrown overboard, as well as other bulk supplies; two ponies died; and the bilge pump was choked by coal dust, so that a constant chain of buckets for bailing had to be maintained for more than a day. Eventually Lieutenant Evans cleared the pumps of coal-dust balls, sea water could be emptied from the ship, and at last, the gale subsided. On December 9, the ship reached the extensive pack ice, but it was a slow journey breaking through to the Ross Sea and an ultimate landing place. Scott's first choice—Cape Crozier on Ross Island—proved impossible, as did Hut Point, the old Discovery base, and Scott eventually selected Cape Evans, 13 miles (21 km) north of Hut Point. Valuable time had been lost through the severe storm and the long journey through the pack, so unloading had to proceed at a good pace using the dog and motor sledges, the ponies, and man-hauling to transport the store ashore. Unfortunately, the third motor sledge plunged through weak sea ice and sank to the bottom. A new base hut was erected, measuring 15 meters by 8 with a height of 5 meters in the centre. According to naval tradition, the crew were separated from the officers and scientists by a central line of packing cases with separate messing facilities. Stables were built for the ponies, accommodation for the dogs, and corners allotted to the scientific and photographic laboratories.

Scott had already decided on the composition of the scientific exploring parties, which were named the Southern, Eastern (later Northern), and Western Parties. Scott led off first with twelve men, ponies, and dogs on January 26, 1911. Their objective was to travel across the Great Ice Barrier (now known as the Ross Ice Shelf) laying caches of food, fuel, and fodder at intervals at least as far as 80° S, to be used by the Polar Party the following year. He was accompanied by Teddy Evans, Wilson, Oates, Meares, Bowers, Cherry-Garrard, Atkinson, the Norwegian ski expert Tryggve Gran, petty officers Crean, Patrick Keohane, and Robert Forde, and Demitri. The Western Party consisted of Griffith Taylor (the leader), Debenham, Wright, and Petty Officer Edgar Evans. They headed for the mountain ranges west of McMurdo Sound to examine the Dry Valleys and the Koettlitz Glacier. The Eastern Party under Campbell consisted of

Priestley, Levick, petty officers George Abbott and Frank Browning, and Able Seaman Harry Dickason. They left in *Terra Nova* for King Edward VII Land at the eastern end of the Great Ice Barrier, but could find nowhere suitable for a base camp and turned west where they might land on the barrier itself. To their astonishment they discovered *Fram* and that Amundsen had established a camp, called Framheim, at the Bay of Whales. The two vessels exchanged entertainment and pleasantries, and Campbell was impressed by Amundsen's camp, which had an extensive library, the luxury of a sauna, and special provision for 110 dogs, all located some 60 miles (100 km) closer to the South Pole than their own base.

Scott's party had difficulties with both the dogs and the ponies, and Atkinson sustained a serious foot injury. They established a cache, which they named One Ton Depot, at 79°29′ S, some 30 geographical miles (56 km) short of their original objective. On the return, a number of the ponies died, and the party was forced to remain for a month at Hut Point, before McMurdo Sound froze over enough to allow them to return to Cape Evans. During this period they were joined by the members of the Western Party. They also learned from a letter left by Campbell of the location of Amundsen's camp, but it was then too late in the year for Scott to alter his own plans for the assault on the Pole. In March they returned to Cape Evans, and the entire party settled in for the long southern winter.

The absence of the Sun during the winter months enforced a leisurely routine on all the personnel in the hut—common mealtimes, regular feeding of dogs and ponies, instrumental weather readings whatever the snow and wind conditions outside, and detailed preparations for the attempt on the Pole once the Sun was again above the horizon. Evening lectures were given by the scientists three times each week, recitals were attempted on the pianola, and Ponting's beautiful slide shows were much enjoyed. In addition, the tradition of producing *The South Polar Times,* a base magazine first put together on Scott's earlier expedition, was continued under the editorship of Cherry-Garrard.

On June 27, 1911, a mid-winter journey to Cape Crozier, on the far side of Ross Island, started in order to allow Wilson to visit a breeding colony of emperor penguins and to collect eggs and possibly embryo chicks. Wilson was joined by Cherry-Garrard and Bowers. The story of this heroic sledge journey was later immortalised in Cherry-Garrard's *The Worst Journey in the World*. The journey was fraught with difficulties—rough ice made sledging difficult as they were hauling food and equipment weighing 757 pounds (343 kg) between them, and the winter darkness hampered navigation. At times the temperature fell to –49°C, and on July 5, it reached a low of –51°C. Eventually they reached the colony, killed three penguins, and collected five eggs, two of which were smashed on the climb back to their camp. No more could be done, as a severe gale blew away their tent and the temporary canvas roof of their snow shelter. By the greatest good fortune Bowers discovered their tent a quarter of a mile away. They set out back on the return journey and arrived at Cape Evans, completely exhausted, on July 31, having covered 116 miles (187 km). It had been one of the most bitterly challenging journeys ever undertaken in Antarctica. For Captain Scott and all the others, it was a portent of the assault on the Pole, and clear evidence of the strength of members of his expedition.

On October 24, 1911, the first stage of the Southern Party was ready, comprising the motor-sledge team led by Teddy Evans, mechanic Bernard Day, Lashly, and steward F. J. Hooper. The two sledges broke down after a short crossing, but far enough to allow the following ponies a lighter load at the beginning of their journey to what was named Corner Camp. Scott set out on November 1 with ten ponies, together with Atkinson, Bowers, Cherry-Garrard, Crean, Edgar Evans, Petty Officer Patrick Keohane, Oates, Wilson, and Wright. Last came the dog drivers Meares and Demetri Gerof, with twenty-six dogs. All three groups rendezvoused at 80°32′ S on November 21.

Scott's route to the Pole was planned to cross the Great Ice Barrier via the established depots to the foot of the Beardmore Glacier and thence to climb to the Polar Plateau via the Beardmore, setting up new depots for the return journey. All the ponies were eventually killed and their meat added to the daily rations or cached, and the remaining dogs taken back by Meares and Demetri to assist with a relief party to meet Scott and the others on their return from the Pole. The ascent of the Beardmore seemed an endless grind—105 miles (169 km) rising to some 10,000 feet (3050 m) above sea level over steeply inclined, heavily crevassed hard ice, often in near-blizzard conditions. It was man-hauling on skis day after day. Although they were driven on by the prospect of their ultimate goal, the severe conditions for such a long period began to take their toll. The low temperatures, dehydration, high altitude, and incipient scurvy weakened even this group of physically strong men.

On December 21, Scott had sent back Atkinson, Cherry-Garrard, Wright, and Keohane, and on December 31, he ordered Evans' team to depot their skis and to continue on foot. This instruction seems strange in retrospect, and, without any reason given by Scott in his diaries, inexplicable. On January 3, 1912, Scott made another unfathomable decision, to increase the number of the polar party from an original four to five, by including Bowers, a tireless and strong man-hauler. This made the tent more crowded and required an increase in the daily food allocation, requiring, therefore, the repacking of stores. In addition, Bowers no longer had his skis, and had to trudge along on foot. But he was a fifth man to help in pulling the sledge. The final polar party consisted of Scott, Wilson, Bowers, Oates, and Petty Officer Evans, representing the lower deck. The others, Teddy Evans, Crean, and Lashly were dispatched back to Cape Evans. In great hardship they reached the Great Ice Barrier, where Evans was found to be suffering from acute scurvy. He managed, with help, to come close to Corner Camp but could go no farther. Lashly stayed with him, and Crean went alone to raise help from Atkinson and Demetri, who were at Hut Point. Evans was shipped back on Terra Nova to New Zealand, where he recovered. Crean and Lashly were awarded the Albert Medal for their bravery.

Meanwhile Scott's party sledged onwards across the Polar Plateau until January 16, when Scott wrote, "The worst has happened." In the distance they could see the outline of a pole, flying a black flag. They feared they had been beaten by Roald Amundsen, and in the nearby tent was a message from Amundsen, and a letter to be sent to the king of Norway. Amundsen, with his fellow Norwegians Olav Bjaaland, Helmer Hanssen, Sverre Hassel, and Oscar Wisting, had attained the pole on December 15, 1911. They had travelled with dog teams from the Bay of Whales, by a new route across the barrier and up the Axel Heiberg Glacier.

Scott made careful observations to confirm the position of the pole, and wrote in his diary the most often-quoted, poignant, and heartfelt cry of any polar explorer: "Great God! This is an awful place, and terrible enough for us to have laboured to it without the reward of priority." In utter despair, the party took photographs of themselves at the pole, and on January 18 started back. "Now for the run home, and a desperate struggle," Scott wrote.

Scott and his companions now had to contemplate their own return. They were dispirited in the extreme, suffering from frostbite and malnutrition; Wilson had an injured leg, Evans' cut hand was not healing, and Oates had a gangrenous foot. At first travel was smooth and rapid, and Scott called a halt on February 8 and 9 to collect some 16 kg of rock and fossil samples, but as they reached the lower Beardmore it was clear that Evans could no longer share the sledge hauling. His harness was taken off, but he fell farther behind and collapsed and died on February 17. As they crossed the Barrier, they hit particularly bad weather and their progress was slowed. Oates was in a bad way with his foot and on March 16 left the tent to make the ultimate sacrifice. His statement "I am just going outside, and may be some time" is one of the most famous in the history of polar exploration. He was never seen again.

The party continued on slowly, but when they were only 11 miles (18 km) from One Ton Depot, they were imprisoned in their tent whilst an exceptionally fierce blizzard blew for some 10 days. There, Scott wrote numerous letters and made his last entry in his diary, dated March 29, 1912. It is likely that the three remaining men—Scott, Wilson, and Bowers—died around that date.

Meanwhile a second Western Party had gone back into the areas west of McMurdo Sound, again led by Taylor, and this time including Debenham, Gran, and Forde. They were picked up in February 1912 by *Terra Nova,* which also collected many of the other expedition members from Cape Evans and returned north to New Zealand, not knowing what had happened to Scott and his party.

At Cape Evans, Atkinson, the senior officer with the disability of Evans, took command. He sent Cherry-Garrard and Demetri south to meet the Polar Party, but a blizzard struck when they reached One Ton Depot, and the two men were not able to travel farther south, ultimately heading back north on March 10. With the departure of *Terra Nova,* the thirteen remaining members of the expedition grew more and more apprehensive about the Polar Party. Then winter set in, and it became apparent that Scott and his companions would not return. On Midwinter Day, June 22, Atkinson discussed their future activities; all agreed it was essential to search the barrier as soon as possible. Accordingly, three search parties had left by October 30, and on November 12 Wright spotted something in the distance. It was a tent, and within they discovered the bodies of Scott, Bowers, and Wilson. The diaries were removed, the tent collapsed, and over it they built a cairn atop of which was a simple cross.

In January 1913, *Terra Nova* returned under the command of Teddy Evans and picked up the remaining men of the expedition, including the members of the Northern Party, who had joined their colleagues at Cape Evans in November 1912.

PETER SPEAK

See also **Amundsen, Roald; British Antarctic *(Terra Nova)* Expedition, Northern Party; British National Antarctic *(Discovery)* Expedition (1901–1904); Debenham, Frank; Dry Valleys; History of Antarctic Science; Norwegian *(Fram)* Expedition (1910–1912); Oates, Lawrence Edward Grace; Photography, History of in the Antarctic; Priestley, Raymond; Ross Ice Shelf; Ross Island; Scott Polar Research Institute; Scott, Robert Falcon; South Pole; Wilson, Edward**

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BRITISH ANTARCTIC *(TERRA NOVA)* EXPEDITION, NORTHERN PARTY

One of the basic plans for Robert Falcon Scott's British Antarctic expedition in *Terra Nova* was to have two supplementary parties to the main geographical one that would head towards the South Pole. One of these, the Western Party, would travel into the mountains west of McMurdo Sound and engage in scientific studies. The other, under the command of Lieutenant Victor Lindsey Arbuthnot Campbell, was to carry out scientific work in King Edward VII Land, east of the Great Ice Barrier (now known as the Ross Ice Shelf). It was known as the Eastern Party and sailed from the new base at Cape Evans in February 1911 in *Terra Nova*. Unable to reach King Edward VII Land, the party tried to find a suitable landing base on the barrier itself. But, upon reaching the Bay of Whales, they found Norwegian explorer Roald Amundsen and his party to have established a base there. With no other suitable anchorage, the ship returned first to Cape Evans and thence north to Victoria Land, where Campbell's party of six—now renamed the Northern Party—was landed at Cape Adare. With the help of the crew of *Terra Nova,* they put up a new hut to winter in and also rebuilt the old huts from Carsten E. Borchgrevink's *Southern Cross* expedition. The ship then sailed for New Zealand.

Along with Campbell, who had been nicknamed "the wicked mate" for his strict naval discipline, were naval surgeon Murray Levick, geologist Raymond Priestley, and three seamen, petty officers George Abbott and Frank Browning, and Able Seaman Harry Dickason. They were about to endure conditions as cruel as Scott's own party had endured. The small group began a disciplined routine of observations into the zoology, geology, and meteorology of the nearby area, and Abbott acted as carpenter and Dickason as cook. They were virtually trapped at Cape Adare for the austral winter, although they did engage in several sledging trips that were disappointing in their results. The men anxiously awaited the return of *Terra Nova,* which arrived on January 4, 1912. Campbell and his party quickly embarked and were taken south to Terra Nova Bay, where they disembarked at Evans Coves on January 8 with just six weeks' sledging rations. Having completed scientific work around Mount Melbourne, they waited to be picked up by *Terra Nova* on February 17. However, the ship did not arrive, although it made repeated attempts to break through pack ice some 30 miles (48 km) out. Campbell realised that they were required to spend another winter in this desolate spot. Their tents had been damaged in a gale and there was no other possibility of a shelter than digging a cave in the snow and ice. A drift was found on the eponymous "Inexpressible Island," and an underground "igloo" was prepared. It was just 12 feet by 9 (3.7 x 2.7 m) in dimension with the ceiling so low that no one could stand upright. The floor was covered by old tent cloths laid over dried seaweed, gravel, and pebbles; some insulation was obtained by forming the cave walls of 12-inch (30-cm) snow blocks. Two door frames were made from biscuit boxes, and the entrance was covered by a sealskin curtain. To one side was a foul latrine. In this confined space the six men cooked, ate, slept, and lived out their days and nights with only a few novels, a Bible, and Priestley's journal for reading matter. Food was obtained by killing seals and penguins stored in a small cache within the cave interior so that preparation consisted of laboriously carving the frozen flesh with hammer and chisel into pieces small enough to place on the primus stove. The blubber lamps gave barely any illumination while smoking so much that it was not long before the cave walls and the explorers' clothing, bodies, and hair were permeated with it. Priestley guarded the few remaining rations they had brought with them, and distributed tiny amounts on a regular basis.

They became gradually weaker through lack of exercise and the debilitating diet; ultimately the entire party had severe enteritis. On September 30, 1912, Campbell decided they must attempt the 200-geographical-mile (370-km) haul back to Cape Evans. Browning and Dickason were too weak to pull a sledge along the sea ice, but on October 29, at Cape Roberts, a food cache was found that had been left the previous year by the Western Party.

Here were biscuits, raisins, tea, butter, lard, and cocoa, and a change of clothing. It was like a wondrous feast to men deprived of food for so long.

Sufficiently revived to continue their journey, they pressed on with a new vigour and reached an empty Hut Point on November 6. Atkinson had left a message for the captain of *Terra Nova,* from which they learned of the fate of Scott and his comrades. The next day they reached Cape Evans to find another hut unoccupied but soon were welcomed by geologist Frank Debenham and the new cook, W. W. Archer. They heard that the others had gone south, as a search party, to look for evidence of the tragedy.

Campbell was promoted to Commander for his leadership of the Northern Party. After serving in World War I, he settled to live in Newfoundland for the rest of his life.

PETER SPEAK

See also **Borchgrevink, Carsten E.; British Antarctic *(Southern Cross)* Expedition (1898–1900); British Antarctic *(Terra Nova)* Expedition (1910–1913); History of Antarctic Science; Norwegian *(Fram)* Expedition (1910–1912); Priestley, Raymond; Ross Ice Shelf; Scott, Robert Falcon**

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BRITISH GRAHAM LAND EXPEDITION (1934–1937)

The British Graham Land Expedition (BGLE) was launched in 1934 on a budget of £20,000, which included a grant of £10,000 from the then British Colonial Office, with the rest raised from public subscription. The expedition was highly cost-effective both in the fields of land exploration and of scientific work in biology, geology, and meteorology.

The expedition was led by the Australian John Riddoch Rymill (1905–1968), who had cut his teeth in polar work in the harsh school of East Greenland under the leadership of H. G. (Gino) Watkins on the British Arctic Air Route Expedition, 1930–1931 (BAARE). Watkins had next planned to lead a trans-Antarctic expedition, but, since funds were not available, he returned to East Greenland with a four-man party in 1932, with Rymill as his second-in-command. Following Watkins' tragic death by drowning while sealing from his kayak in August 1932, Rymill took over the leadership of the party, which carried out useful survey and meteorological work.

Rymill now took up the Antarctic challenge, but was persuaded by advisors in London to lead a survey and scientific expedition to Graham Land, the northern part of the Antarctic Peninsula, lying to the south of the Falkland Islands.

There were sixteen members of the expedition, four of whom were seconded on full pay from the Royal Navy and two from the Army. The expedition ship was the three-masted topsail sailing schooner of 130 tons, named *Penola* after Rymill's family station in South Australia. In command of Penola was Lieutenant Robert Edward Dudley Ryder, RN (1908–1986). With little fanfare, *Penola* sailed from the port of London on September 10, 1934, with Ryder appalled by the sloppiness of his mainly university crewmen. Ryder demanded things be in very "ship-shape" fashion, but eventually an understanding was reached, with Ryder relaxing a little and the civilians raising their standards drastically.

Rymill was a born leader of men. He stood 6'4″, of magnificent physique with immensely broad shoulders. His personality and bearing, and his schooling under Watkins, were such that his tactful suggestions passed for orders. This is the ideal form of leadership on a civilian operation with modest numbers. Withal he was an expert dog-driver and skier, an experienced air pilot, and a competent surveyor.

Most members of the BGLE would have stood out in any company. Ryder was an able marine surveyor whose surveys of harbors off the west coast of Graham Land are still used on British Admiralty charts. The first mate of *Penola* was James Hamilton Martin (1900–1940), an outstanding seaman who, after service as an officer in the Grenadier Guards near the end of World War I, indulged his passion for sailing, including as a seaman and then as boatswain in RRS *Discovery* on the British Australian New Zealand Antarctic Research Expedition, 1929–1931, for which he was awarded the Polar Medal in bronze.

The expedition doctor was Surgeon Lieutenant Edward William Bingham (1901–1993), who had previously served on the BAARE. A number of other members of the expedition also had previous polar experience. From the BAARE there were Wilfred Edward Hampton (1907–1994), experienced pilot and engineer of the BGLE's light aircraft, and Alfred Stephenson (1908–1999), expedition chief surveyor. From expeditions to Svalbard there were Colin

Bertram (1911–2001), the seal specialist; Launcelot Fleming (1906–1990), the expedition geologist and chaplain, jocularly called the "Bishop of the Antarctic"; and Brian Burley Roberts (1912–1978), the expedition ornithologist. The youngest member of the expedition was Duncan Carse (1913–2004), who, at the age of 21, transferred from RRS *Discovery II* to *Penola* as a deckhand (later radio operator) in the Falkland Islands.

At Port Stanley, in the Falkland Islands, *Penola* underwent refitting before sailing on January 7, 1935, for Port Lockroy, Wienckle Island, where the expedition's aircraft (a single-engine de Havilland Fox Moth), the heaviest of the stores, and the dogs for sledging had been dropped off by *Discovery II*. Due to engine problems, they were not able to take the ship much farther into the ice, so they wintered at the Argentine Islands, building a two-story living hut with an attached airplane hangar, and allowing *Penola* to freeze in for the winter.

Throughout 1935, the expedition members explored, surveyed, and charted the area; made scientific observations and built up collections; and raised and trained the dogs. Early in 1936, *Penola* sailed to Deception Island, and on her return the base was moved farther south, to Marguerite Bay. Here a party of nine men and ninety-three dogs was left for a second winter while the ship returned to the Falkland Islands.

Extensive surveying was planned from the new base, beginning with an aerial reconnaissance program. Then, following winter depot-laying sledge journeys, a large program of exploration was carried out, examining the fjord system of Marguerite Bay, the plateau of central Graham Land, and the areas surrounding George VI Sound, a large channel separating Alexander Island and the Antarctic Peninsula. In early 1937, Penola returned to pick up the shore party and pack up the southern base.

The expedition returned to England in 1937 with no fanfare at all, because clouds of war were gathering in Europe and because the excellent organization of the expedition precluded the disaster and loss of life that attract publicity. The BGLE brought back a rich harvest of scientific results in the fields of survey, geology, and biology. Above all it established that the Antarctic Peninsula is in fact a peninsula and not an archipelago, as postulated by Sir Hubert Wilkins on his flight southwards from Dundee Island in 1929, and by Lincoln Ellsworth. The BGLE also established the insularity of Alexander Island as separated from the Antarctic Peninsula by the wide channel of King George VI Sound.

All members of the BGLE received the Polar Medal in Silver with Antarctic clasp 1935–1936, or second clasps to Polar Medals already held, and all are commemorated in place names on or off the west coast of Graham Land. Several of them went on to establish international reputations. Ryder was awarded the Victoria Cross "for valour" as commander of the Royal Naval force in the raid on St. Nazaire in 1942. He retired from the Royal Navy as a captain in 1950 to become a Conservative Member of Parliament.

After service in World War II, Bingham was appointed the third field commander of the Falkland Islands Dependencies Survey (now British Antarctic Survey), and established its farthest south-base at Marguerite Bay on the west coast of Graham Land. Fleming became director of the Scott Polar Research Institute (SPRI) before becoming Bishop of Portsmouth, then Bishop of Norwich, and finally Dean of Windsor and confidant of HM Queen Elizabeth II. Bertram succeeded Fleming as the director of SPRI. Roberts later became head of the Polar Regions Section of the Foreign and Commonwealth Office, where he played a leading role in Antarctic affairs internationally, including the development of the Antarctic Treaty. And Carse led a series of expeditions, 1951–1957, to map South Georgia. The map he produced was of great value in the Falkland Islands conflict of 1982.

GEOFFREY HATTERSLEY-SMITH

See also **Antarctic Peninsula; Antarctic Treaty System; British Antarctic Survey; British, Australian, New Zealand Antarctic Research Expedition (BANZARE) (1929–1931); Dogs and Sledging; Ellsworth, Lincoln; South Georgia; Wilkins, Hubert**

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BRITISH IMPERIAL EXPEDITION (1920–1922)

This expedition was originally conceived by its leader John Lachlan Cope in 1919 as involving up to fifty people, making it one of the largest planned until that date. In fact, it eventually became the smallest ever to winter in Antarctica, consisting of just two men—Thomas Wyatt Bagshawe, a 19-year-old geologist, and Maxime Charles Lester, a 22-year-old Royal Naval Reserve lieutenant with some surveying experience—who spent a year, from January 1921, at Waterboat Point on the northwest coast of Graham Land, Antarctic Peninsula.

The first, most grandiloquent plan drawn up by Cope, who had served as surgeon and biologist of the Ross Sea party of Ernest Shackleton's 1914–1917 Imperial Trans-Antarctic Expedition, included the circumnavigation of Antarctica from a base in the Ross Sea using Scott's old ship *Terra Nova,* the first flight over the South Pole, and an extension of the survey of the west coast of the Weddell Sea beyond the limit reached by Otto Nordenskjold's 1901–1903 Swedish South Polar Expedition, to join up with the discoveries of William Speirs Bruce, Wilhelm Filchner, and Shackleton on the south and east coasts. A more modest proposal, without the circumnavigation, but still including a plan to take twelve war surplus planes to the Ross Sea and fly them to the South Pole, attracted the interest of Hubert Wilkins, an experienced aviator who had spent four years in the Arctic with Vilhjalmur Stefansson's 1913–1918 expedition.

However, Cope failed to find financial backing even for this reduced objective, and so was forced to abandon the planes, retaining only the third component, a dog sledge journey south from Snow Hill Island along the western and southern shores of the Weddell Sea. Even so, the expedition could not afford its own ship, and had to rely on whaling ships operating in the Peninsula area for transport.

The four members of the expedition, with rather meagre supplies and only eight dogs, finally met at Deception Island on Christmas Eve 1920, intending to find a whaler to take them to Hope Bay on the tip of the Antarctic Peninsula, from where they would make their way by lifeboat to Snow Hill Island. However, Hope Bay was inaccessible due to ice, and the whaler deposited them on January 12, 1921 on a tiny point at the northern entrance to Paradise Bay on the Danco Coast, at 64°48′ S, 62°43′ W. Still, they hoped to be able to reach the Weddell Sea coast and follow their original plan, but it soon became obvious there was no way across the mountainous spine of the peninsula. With the third and final component of the expedition at a dead end, Cope and Wilkins opted to return home by whaling ship, but the two younger men volunteered to stay for the winter; they had come to sample the Antarctic, and they were not going back until they had done so. Before his hurried departure on March 3, 1921, Cope agreed to try and find a ship to relieve the pair next year; failing that (as indeed turned out to be the case), the whaler captain agreed to take them home at the end of the following season.

Left to their own devices, Bagshawe and Lester made their home in a stranded waterboat, 30 feet (9 m) long by 10 feet (3 m) wide, after which the Point was named. With their only tools—a saw, two geological hammers, a chisel, and some pocket knives—and with nails "every shape other than straight" extracted from packing cases, they extended the boat with canvas and boards lined with spare eiderdowns to provide a tiny "lounge" and kitchen. Despite ingenious improvisation—using sealskin for door hinges‘ making a shovel from a kerosene tin, candlesticks from cigarette tins, and an oven from a biscuit tin—their living conditions were squalid in the extreme. Their cramped quarters leaked in the frequent icy rain, their stove made from an old oil drum either refused to light or smoked them out, and their diet consisted almost entirely of seals and penguins, which at least helped them to avoid scurvy. By July 1921, they had made the best they could of their situation, with such civilised comforts as a linen tablecloth for meals and a gramophone for musical evenings. With only candlelight, they could not read in the evenings, and had no communication with the outside world at all. Their isolation was increased by the confines of their location, surrounded by water on three sides and a 100-foot (35-m) glacier wall on the fourth. With limited equipment and manpower they could not venture far along the coast on the unreliable sea ice, nor could they use the dogs in the rough terrain inland. The longest expedition they managed was 6 miles south along the edge of the glacier, a 12-hour return trip on August 24.

Nonetheless they completed a substantial scientific program. Throughout the year they maintained a two-hourly meteorological log, using a screen built by the whaling ship's carpenter, with a homemade wind vane on top, compiling the first complete annual record of weather conditions in the region. In addition, Bagshawe collected geological and biological specimens, and kept a daily ice log, while from October 30 for 30 days they kept an hourly tidal log, taking alternate 6-hour watches at the tide gauge, a calibrated half oar attached to a boulder-filled wooden barrel. Their greatest interest, however, was in the Adélie and gentoo penguins that nested nearby; Bagshawe made extensive notes on their behaviour, to the point of identifying individuals by name, and, on leaving, he found he missed his friends very much. Unfortunately, this work was not published until 1939, as appendices to Bagshawe's narrative of the expedition. As pioneers of such research in this region of Antarctica, their results would have been helpful to their successors, just as they found the reports of Jean-Baptiste Charcot's two earlier expeditions.

When Captain Andersen in the whaler Svend Foyn finally came to take them home on January 13, 1921, after a year and a day at Waterboat Point, they both "felt miserable as we watched the hut disappear from sight...it was to us a haven of comfort" and Bagshawe summed up his experience as one of "sheer delight" (Bagshawe 1939).

In a fitting tribute to the two members of this bizarre expedition, Frank Debenham, first director of the Scott Polar Research Institute, commented, "Never were there such devoted scientists...these two young men possessed that quality so annoying to the great Napoleon, of not having the sense to know when they were defeated" (Bagshawe 1939).

LOUISE CROSSLEY

See also **Antarctic Peninsula; Aviation, History of; Gentoo Penguin; Ross Sea Party, Imperial Trans-Antarctic Expedition (1914–1917); Swedish South Polar Expedition (1901–1904); Wilkins, Hubert**

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BRITISH NATIONAL ANTARCTIC *(DISCOVERY)* EXPEDITION (1901–1904)

The British National Antarctic Expedition, Robert Falcon Scott's (1868–1912) first expedition, was one of the most important endeavors of the Heroic Age and introduced several of the great figures to the Antarctic regions. The effort set the stage for British involvement in the period until 1922, including offering insight into the tragic events of the second Scott expedition. The scientific results mark it as one of the most productive of the early-twentieth-century expeditions.

The *Discovery* expedition, as it was also known, owed its existence to the strong will of a single person. Sir Clements R. Markham (1830–1916) was determined to combine two of his great loves—polar exploration and the Royal Navy—to create the crowning achievement of his term as president of the Royal Geographical Society (RGS). He hoped to send forth a national Antarctic expedition that would revive the adventurous spirit of his fellow countrymen and place Great Britain once more at the forefront of scientific exploration. Virtually from the moment of his election as president, he used the RGS as a vehicle to carry out his plan.

At first his efforts at private funding were met with indifference. He subsequently attempted to get the British government to underwrite the cost but found no support in that arena. Eventually he combined his efforts with the Royal Society, and together they campaigned to launch the endeavor. The breakthrough Markham had hoped for came in March 1899 when Llewellyn Longstaff offered the RGS a £25,000 contribution. This donation finally allowed the two royal societies to petition the government and acquire sufficient funding for the voyage.

Markham was determined to have a purpose-built ship and discounted the evidence that a whaling vessel would have been sufficient for the task. Thus, *Discovery* was constructed in Dundee, Scotland (where it has now returned as a major tourist attraction), and launched in March 1901. The vessel was not without its problems. Throughout the first voyage the ship was slower than expected and was plagued by a series of leaks.

Sir Clements also selected the commander of the expedition, a young naval lieutenant, Robert Falcon Scott. Controversy still exists regarding the means by which the appointment took place, whether Scott or Markham took the lead in bringing about the decision. The choice of Scott was not without opposition from elements within the Royal Navy. A few years earlier, Markham had suggested the qualifications for an ideal leader for this kind of endeavor. Although

Scott did not really match that profile, once Sir Clements made his mind up, he was tenacious in his defense of Scott, who was subsequently approved by the committee that oversaw the direction of the expedition.

Moreover, prior to sailing, a huge controversy erupted, which in the short run allowed Markham to triumph, but in the longer term may have had unfortunate consequences. J. W. Gregory (1864–1932) had been chosen as the scientific director of the expedition, and once his appointment was secured, he attempted to ensure he would have control of all scientific work. In general, he found support from the Royal Society. Together they preferred an expedition that placed science above adventure or geographical discovery. Not so Markham, who, as a consummate committeeman, finagled the situation and succeeded in establishing that the captain of the ship, Scott, would be in absolute command. The men of the Royal Society were miffed and lived to see a degree of revenge meted out against the president of the RGS. For his part, Gregory found the newly established conditions intolerable and resigned. George Murray (1858–1911) became the temporary scientific leader, but in the end Scott essentially performed those duties himself. Although it was not part of the reason he was chosen to command, Scott made a good scientific leader.

However, as Peter-Noel Webb has pointed out, Gregory's loss might be greater than some historians have noted, for his knowledge and expertise might have enhanced the results of the expedition, particularly in the eventual development of the theory of plate tectonics.

Among those chosen as members of the professional staff and ship's complement were young obscure men who subsequently became among the great figures in polar history. Edward Wilson (1872–1912), a young physician only recently back from tuberculosis treatment in Switzerland, could not pass the physical examination. But Scott had been so impressed with Wilson that he insisted he be appointed. Ernest Shackleton (1874–1922) had fortunate personal connections to the Longstaff family and secured a place, while another financial backer recommended Albert Armitage (1864–1943), who served as the pilot and second-in-command. Tom Crean (1877–1938), Bill Lashly (1868–1940), and Ernest Joyce (1875–1940) each made a first trip to the Antarctic on this voyage. The scientific staff, meanwhile, was enriched by Louis Bernacchi (1876–1942), who had served on the *Southern Cross* expedition and who along with Armitage and surgeon Reginald Koettlitz (1861–1916) was among the three who had previous polar experience.

Preparations completed, *Discovery* sailed from England in July 1901 and proceeded to Christchurch, New Zealand, via Cape Town. The ship did not live up to expectations in terms of sailing ability and coal consumption, but more annoying was the constant leaking. At Cape Town it got a substantial refitting at the cost of the Royal Navy, which lent every assistance to Scott and his men. Departing South Africa, Scott opted to skip a previously scheduled stop in Melbourne and proceed directly to New Zealand.

As was the case with other British Antarctic expeditions of this period, the people of New Zealand proved gracious hosts. The time ashore there was not only a welcome respite to the men but also a time to make the ship ready for the voyage south. *Discovery* was put in dry-dock to stop the leaking, but subsequent sailing indicated that the problem remained. Physicist Louis Bernacchi joined the staff at this time, as did another great figure in polar history when Crean was added to the roster. Throughout the stay the scientists continued their work and made arrangements to coordinate experiments that would take place in both New Zealand and the Antarctic.

Regrettably the departure was marred by tragedy as a sailor fell to his death from the top of the mast as the ship was departing Lyttelton, an accident that bears an uncanny parallel to one on Jean Charcot's (1867–1936) first expedition.

The journey to the Ross Sea was accomplished without undue difficulty, and a stop was made at Cape Adare, where Bernacchi was able to visit his former quarters from the *Southern Cross* expedition. Scott took his ship to Ross Island and then out along the Ross Ice Shelf, known at the time as the Great Ice Barrier. Pushing eastward the explorers reached the end of the Ross Ice Shelf and spied new territory, King Edward VII Land, one of the most significant geographical discoveries of the voyage. Turning westward again, at an inlet in the wall of ice, the men landed and launched a balloon to give them a better view of the area. The balloon proved to be of limited use, and, after several men went aloft, the experiment was not repeated.

Scott took his ship back to McMurdo to a place known now as Hut Point and there prepared his ship to be frozen in for the winter. On shore the men erected a hut (still standing), which served as a storage and work area for the expedition. The remainder of the fall was spent establishing the scientific work and in several short forays.

The first attempt at sledging showed the degree to which the party was less prepared than it might have been. What would later be considered a short and not-terribly-difficult sojourn was made, but when the men returned, they were exhausted and spoke of how arduous the journey had been. This experience should be kept in mind when assessing later journeys when the men were hardened to the life of man-hauling in the Antarctic.

One party was sent to Cape Crozier in early March 1902 to leave a message as agreed before departing from England. Scott had planned to lead this group himself but a skiing injury made that impossible. The party encountered difficulties, and Lieutenant Charles Royds, who was in charge of the group in place of the injured Scott, decided to send Lieutenant Michael Barne back with a party of bluejackets. On their return, this party became separated into two teams, and one of the sailors, George Vince, died in an accident. Others might well have died, had Frank Wild (1874–1939) not led the remainder of his group back to the safety of the ship.

From the moment they arrived at Hut Point, the scientists launched their research programs, and these continued throughout the winter. For the entire party, the coming of winter was a mixture of excitement with concern about surviving the long polar night. *Discovery* was locked into the ice 500 miles (800 km) farther south than any previous group, and surviving the winter was not a guaranteed outcome. April 1902 saw the disappearance of the sun and onset of real winter.

A regular routine was maintained throughout the dark months with a fairly light workload for the men, while the officers and scientists were kept busy with a variety of tasks. In effect, Scott became his own scientific director and proved a very good one, showing considerable interest in the scientific work and keeping a light hand on the direction of the research.

A strict class structure was maintained. Officers and men had separate quarters and different food, tobacco, and work assignments. For the purpose of the trip, the scientists were considered officers and gentlemen.

Diversions were an important part of these months, with regular lectures, musical programs (including some vaudevillian efforts), and the publication of a literary magazine, *The South Polar Times*. Such journals were a staple of nineteenth-century British Arctic expeditions. This writing effort is an example of how Markham transmitted to these voyages many of the experiences of those previous endeavors. Furthermore, their literary skills showed the degree of influence that the educational reforms of late-nineteenth-century Great Britain had had on the working classes. Both the officers and the men contributed to this periodical, which was edited by Shackleton, who showed the same flair with this as he had with his other work on the expedition. Wilson contributed exquisite drawings, and the single copy of the work was read first by Scott and then aloud to everyone else. After the voyage, a limited edition of the magazine was published; it commands a hefty price today.

The ship contained a fine library, and the tastes of both the wardroom and the mess deck were satisfied. The winter passed without serious mishap, although several times men were lost for periods of time trying to maneuver near the ship in bad weather.

Spring officially began with the departure of a sledging party from the base in early September 1902, and the summer of 1902–1903 contained a full program of activities. The first few sojourns demonstrated that the men had much to learn about sledging and that their management of the dogs lacked expertise.

At one point, with many of the ship's company, including Scott, out on sledging trips, Armitage's party returned with some of his men suffering from scurvy. This one opportunity for leadership showed Armitage to good advantage. He took immediate and decisive efforts to attack the problem, including a private and direct conversation with the cook, who had previously shown no inclination or ability to prepare seal, a principal source of fresh food in the region. Regrettably, that conversation was not recorded, but after it, the cook demonstrated great skill and enthusiasm in his preparation of seal. A further crisis was averted.

The principal effort that summer was an attempt on the South Pole. Scott had no real expectation of reaching ninety degrees south, but was determined to make a credible effort. Taking with him Wilson and Shackleton, the three men plodded south, using a combination of dogs and man-hauling for transport. The dogs quickly showed signs of illness and almost certainly were done in by the food they were fed. Their poor performance, combined with Markham's insistence that man-hauling was "the true British way," established in Scott's mind that dogs were not the answer to travel in Antarctica. Once the dogs had all died, the trio continued on their own.

Scott was determined to do his duty, which in this case was to proceed south until the last day of 1902. The appearance of scurvy in the three men did not deter him, as he pressed on until 31 December, when the party reached 82°17′ S before turning back. En route north, all three men were severely affected by the disease, but Shackleton was, by far, the most greatly weakened. Shackleton coughed blood, had difficulty in breathing, and showed a steady deterioration of strength. At one point, Wilson believed that his companion would die. However, when they turned north, with the wind at their back, they rigged a sail for the sledge, and Shackleton was able to ride for a short while on the sledge, having by that time been relieved by Scott of man-hauling. When the trio arrived back at Hut Point, all were played out and required bed-rest to recover.

When Scott returned, he found that the relief ship *Morning* had arrived under the command of William Colbeck (1871–1930), of *Southern Cross* experience. This relief had long been part of Markham's plans, although he had not been terribly open about it when he had promoted the expedition. The ice had not broken up, and *Discovery* was held fast, 10 miles (16 km) from open water. Although Scott continued to hope that warm weather in the late summer might free his ship, it remained imprisoned for another winter.

When the relief ship departed, several men were sent back to England, including Shackleton. H. R. Mill (1861–1950), the great polar historian, saw this decision as the defining moment in Shackleton's life. Some authors have seen Shackleton's dismissal as being based on Scott's jealousy or fear of being outshone by his third lieutenant. Scott's relationship with Armitage and the offer to let the latter return with the relief ship would seem to support this thesis. While untoward motivations may have played a part, Scott's decision to send invalid Shackleton home was largely based on Scott's (mistaken) belief that Shackleton lacked both the stamina and the pluck for polar work.

The second winter passed in much the same manner as the first, although the men were no longer as taken with the novelty of their surroundings as they had been the previous year. Bernacchi took over the editing of *The South Polar Times,* and another series of the magazine enlivened the darkness.

During the third summer season, Armitage was excluded from the important sledging work and left to direct the freeing of the ship from the ice by cutting a channel through the ice. Such a project was hopeless. Important sledging work was, however, accomplished. Royds led a party to Cape Crozier to investigate the emperor penguin rookery there. Perhaps most important was the trip that Scott made accompanied by Lashly and Evans to the Polar Plateau in Victoria Land. The insight that Scott gained into the psyche of two of the finest bluejackets of the Royal Navy broadened his view of his men more than all of his previous naval experience. Lashly's coolness in a disaster saved the lives of his two companions and added to his reputation as one of the great minor figures of the Heroic Age.

While the relief brought by *Morning* in 1903 was not necessary for the survival of the men, back in England, Markham insisted on a second relief effort. His attempts to raise by subscription funding for a second relief expedition were insufficient. Regrettably, Markham overplayed his hand, and, in language more histrionic than accurate, berated the government for not coming to the rescue of Scott's men. Prompted by backstairs actions on the part of some members of the Royal Society, the government of Prime Minister A. J. Balfour responded, but in a way quite unintended by Markham. The government agreed to rescue Scott, but demanded that Sir Clements surrender all control or influence over the relief.

The government then launched a hugely overpriced and perhaps overdone rescue attempt that involved two ships and two superb captains, Colbeck again, and Henry McKay, an Arctic veteran of formidable reputation. *Morning* was used again, and the government quickly refitted and towed to New Zealand a sturdy whaler, *Terra Nova*.

The rescuers arrived at McMurdo Sound to find that 18 miles (29 km) of ice separated them from *Discovery*. All attempts to cut a path through to Scott's ship had proven impossible. As the ice began to break up, McKay smashed his ship into the wall of ice to break through. Until virtually the last moment, it appeared that the effort would be fruitless, but suddenly the crashing efforts of McKay, combined with explosives and the help of nature, freed *Discovery*. The three vessels floated together in a little pool of water off Hut Point.

Although *Discovery* ran hard aground shortly after being liberated, the three ships departed McMurdo Sound and returned to New Zealand, although they did not travel together because of the different sailing abilities of the vessels.

The British National Antarctic Expedition was one of the most important expeditions of the Heroic Age, and its scientific accomplishments indicate that this voyage was a first-rate effort. The eleven volumes of scientific results attest to the contributions made by Scott's men and compare favorably with other contemporaneous efforts. Scott proved a fine scientific leader, and this voyage introduced to the Antarctic men whose names live on in legend in the annals of polar history: Scott, Wilson, Shackleton, Wild, Crean, and Lashly. But for other later circumstances, men like Armitage and Skelton might similarly be enshrined. The shortcomings of this endeavor owe much to the influence of Markham and his incorrect belief that nineteenth-century British Arctic methods were the standard of behavior and could not be improved upon. For many of those things for which critics blame Scott, the faulted behavior can usually be traced to Markham. For a pioneering effort, the officer and men of *Discovery* had every reason to feel proud of what they accomplished.

T. H. Baughman

See also **British Antarctic *(Southern Cross)* Expedition (1898–1900); British Antarctic *(Terra Nova)***

Expedition (1910–1913); Dogs and Sledging; French Antarctic (Français) Expedition (1903–1905); History of Antarctic Science; Markham, Clements; Photography, History of in the Antarctic; Ponies and Mules; Ross Ice Shelf; Ross Island; Royal Geographical Society and Antarctic Exploration; Royal Society and Antarctic Exploration and Science; Scott, Robert Falcon; Shackleton, Ernest; Wild, Frank; Wilson, Edward

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BRITISH, AUSTRALIAN, NEW ZEALAND ANTARCTIC RESEARCH EXPEDITION (BANZARE) (1929–1931)

On July 3, 1925, Australian Prime Minister Stanley Melbourne Bruce saw a delegation from the Australian National Research Council (ANRC), which urged that Australia should act, in concert with Britain, to secure for Australia the administration of Antarctica between 90° and 160° E, using as part justification the geographical results of the Australasian Antarctic Expedition (AAE, 1911–1914). Bruce said that the government would pursue these ends through appropriate channels. The following year, the Imperial Conference of Commonwealth countries, meeting in London, considered the question, listing areas of Antarctica within the "Australian quadrant" (from 45° to 160° E) that might be annexed on the basis of nineteenth-century British sightings or exploration by expeditions under Douglas Mawson and Robert Falcon Scott, including Enderby Land (45°–53° E), Kemp Land (58°–60° E), Queen Mary Land (86°–101° E), Wilkes Land (131°–135° E), King George V Land (142°–153° E), and Oates Land (157°–159° E). Although the Conference advocated further exploration and research in these regions, no schemes to plant the flag and read proclamations were mooted.

With Australian government approval, the ANRC set up an Antarctic Committee, which included, besides Mawson and John King Davis (captain of the expedition ship *Aurora* during the AAE), prominent scientists and government representatives, with power to act and advise. It was proposed to use Scott's old ship, *Discovery,* undertaking landings and flag-raisings along indicated parts of the Australian quadrant on the assumption that these would subsequently be placed under Australian control. They advocated a second season in the Antarctic if necessary, a scientific program, and use of a ship-based seaplane. The Australian government gave the go-ahead on October 11, 1928. Funding came largely from private sources: £20,000 from chocolate millionaire Sir Macpherson Robertson (or Mac-Robertson), \$40,000 (£8500) from Randolph Hearst for the American press rights, and smaller amounts from other quarters. The Australian government provided £14,000 and the government of New Zealand £2500. Thus, *Discovery* to one side, the British, Australia, New Zealand Antarctic Research Expedition (BANZARE) received more support from the United States than from Britain. Mawson set up a London Committee and oversaw the ordering of equipment and provisions. The British lent *Discovery* for two seasons.

A barque with auxiliary steam engine, *Discovery* rolled badly and required 50 tons of coal to be kept as ballast, limiting the steaming range. A second problem was the command structure, decided upon by the Australian Committee guided by Mawson: Mawson as expedition commander, and Davis as second-in-command and master of the ship only when Mawson was not on board, since it was a ship expedition. Thus, while Davis was the captain, he did not command. He merely had a veto power over Mawson's instructions if he thought those instructions endangered the ship. This led to much squabbling during the first season (summer 1929–1930) and to Davis' refusal to continue for the second season (summer 1930–1931).

Mawson knew that Norwegians under Hjalmar Riiser-Larsen on *Norvegia* intended to make landings and claim territories in the general area of Enderby Land and Kemp Land. For this reason, he started from Cape Town rather than from an Australian port. *Discovery* left Cape Town on October 19, 1929, heading southeast. After securing botanical and geological collections at Îles Crozet, they proceeded to Îles Kerguelen, where they made scientific observations and collections while the long job of recoaling was carried out. It can be argued that Mawson wasted time at Îles Crozet. Prime Minister Bruce's secret instructions of September 12, 1929 stressed planting the flag and reading the proclamation of annexation. Economic and scientific goals were to be secondary. Yet even so they did not make directly for Antarctica but for Heard Island, where they spent 9 days inspecting flora and fauna, surveying, dredging for marine life, and collecting geological specimens. Making southeast from Heard Island on December 4, *Discovery* pioneered the echo-sounding of the long undersea ridge running from Kerguelen past Heard Island to Gaussberg in Antarctica (the Banzare Rise).

Attempts to reach Enderby Land were thwarted by heavy pack ice. Arguments flared between Mawson and Davis over ways to get around or through it. These arguments were noticed by the other members of the expedition, who included the photographer Frank Hurley and a range of scientists. The Gipsy Moth biplane, equipped with floats, was set up and flying by December 31, but no land was clearly discerned until a flight on January 5, 1930, with Mawson in the forward (passenger) seat. This flight gave him his first extensive sighting of what he would name Mac.Robertson Land. They sailed on westward past Kemp Land (unseen) towards Enderby Land, learning by wireless cable that the Norwegians had claimed territory there the previous month. Later, in the interests of British–Norwegian relations, Mawson was allowed to claim the Enderby Land and Kemp Land coasts, although he had not landed there. The closest they came to Enderby Land was a small island in sight of it, named Proclamation Island, on the peak of which Mawson claimed for the Empire full sovereignty of Enderby Land, Kemp Land, and Mac. Robertson Land (47–73° E). On January 14, they met *Norvegia,* which carried two seaplanes and had had more success. During the following days there were additional flights from *Discovery,* this time over the continent, and more land was claimed (around Cape Ann), but coal was running low and on January 26 they headed north.

The second BANZARE cruise achieved greater results. *Discovery* was now captained by K. N. MacKenzie. On November 22, 1930, they set out from Hobart (Tasmania), proceeding via Macquarie Island to Cape Denison in Antarctica (the main base during the AAE), thence westwards, charting the coast of Adélie Land and discerning during flights in the Moth what Mawson named Banzare Land and Sabrina Land (January 1931). Early February saw them off the coasts of what Mawson named Princess Elizabeth Land and, farther west, Mac.Robertson Land (these discerned from the air). Conditions this year permitted the ship to come closer to the land. New features were charted, known features charted more accurately, new mountain ranges observed, and landings made on the mainland on February 13 and 18 (at Scullin Monolith and Cape Bruce). With coal reserves low, the ship then proceeded for Australia across the Banzare Rise, the cruise ending at Hobart on March 19, 1931. Its extensive discoveries and claims, augmenting the superb geographical achievements of the AAE, provided the grounds for the Australian Antarctic Acceptance Act of 1933. This became law in 1936, establishing (with British agreement) the Australian Antarctic Territory, that vast slice of the Antarctic "cake" running from 45° to 160° E, with the sole exception of the French Terre Adélie.

As a result of the oceanographic program, a continuous undersea land-platform around a third of Antarctica was clearly demonstrated, establishing the continuity of land of continental dimensions beneath the ice plateau, in contradistinction to a series of islands cemented by the polar ice cap. This left unresolved whether there were not two continents beneath the ice, riven by a channel from the Weddell Sea to the Ross Sea, a question then being answered by the work of Richard E. Byrd.

PHILIP AYRES

See also **ANARE/Australian Antarctic Division; Antarctic: Definitions and Boundaries; Australasian Antarctic Expedition (1911–1914); Aviation, History of; Byrd, Richard E.; Crozet Islands (Îles Crozet); Davis, John King; Heard Island and McDonald Islands; History of Antarctic Science; Kerguelen Islands (Îles Kerguelen); Mawson, Douglas; Photography, History of in the Antarctic; Scott, Robert Falcon**

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BRUCE, WILLIAM SPEIRS

Regarded as the principal Scottish polar explorer, William Speirs Bruce was, in fact, born on August 1, 1867, at 43 Kensington Gardens Square in the Paddington district of London. He moved to Scotland to attend a summer school in natural history organised by the University of Edinburgh in 1885, and there came into contact with many of its natural scientists. He decided then to withdraw from his intended course of study in medicine at University College, London, and transferred his allegiance to Edinburgh, its city and its academic life. From this time he maintained Scotland as his adopted home, and gradually became a fervent Scottish nationalist. He did have strong family links with Scotland; although his mother, Mary Lloyd, came from Wales, his father, Samuel Noble Bruce, had a long line of Scottish ancestry. William Bruce's grandmother was Charity Isbister from the Orkney Islands, and his paternal grandfather, the Rev. William Bruce, was born in Glasgow in 1799 and became a preacher in the newly formed Swedeborgian church, taking a ministry in Dundee before moving to Hatton Garden in London. The future polar explorer's middle name, Speirs, derived from another Scottish relative, and it has given rise to some confusion in spelling, being often misspelled as "Spiers" or "Spears."

Bruce was the fourth child in a middle-class family of eight children and had one younger brother. His birth certificate shows his father as a surgeon, but he was, in reality, a physician conducting a general practice in one of the wealthiest parts of London. The family later moved nearby to Holland Park, 18 Royal Crescent, and lived there for many years. Bruce grew up in a prosperous Victorian family with a retinue of servants, a coachman, and nursemaids. He was educated privately at home and was frequently taken by his nursemaid to nearby Kensington Gardens and the Museum of Natural History. His father attributed William's love of natural history to these events. It was a beginning, but his truly formative influences would come later in Edinburgh.

Bruce's education was continued at a progressive boarding school, Norfolk County School, North Elmham. He continued his studies of natural history where he would undoubtedly have come into contact with the new ideas of Charles Darwin, for the famous *Origin of Species* had been published in 1859. In 1886, he attended two summer schools in Edinburgh. The summer schools took place at the Royal Scottish Marine Station, Granton, close to the Firth of Forth, making use of a canal barge, *Elizabeth,* affectionately known as The Ark, for laboratory classes. Here he came into contact with the eminent environmentalist and teacher of the holistic method Patrick Geddes.

At the University of Edinburgh, Bruce had classes with such illuminati as professors P. G. Tait, John Arthur Thomson, Sir John Young Buchanan, and Sir William Turner. He learned the rudiments of anatomy, physiology, biology, and zoology. At Granton, he also came into contact with the prestigious zoologist Sir John Murray, who had been on the *Challenger* Expedition, the first of the major scientific expeditions to sail around the world. Murray was editing the Challenger Reports, and Bruce was enrolled to help, on weekends, in their compilation. Bruce was gaining an enviable training in natural history, oceanography, and exploration from the finest group of experts in Britain of the time. In addition to these natural philosophers, Bruce formed an association and friendship with other environmentalists: Sir Alexander Buchan, a pioneer meteorologist, and Hugh Robert Mill, librarian of the Royal Geographical Society of London.

In 1892, Bruce saw an opportunity to explore the Antarctic and enlisted as surgeon on Balaena, one of the fleet of the Dundee Whaling Expedition, bound for the Southern Ocean, to search for the Greenland or "right" whale. He took with him a small collection of scientific instruments to record the weather and the nature of the sea waters. Although the expedition was a failure in sighting whales and the science was less than adequate, it gave Bruce a taste for polar regions: "I am burning to be off again anywhere, but particularly to the far South where I believe there is a vast sphere for research," he wrote to Mill on his return in 1893. He abandoned his university studies and was offered a post, by Alexander Buchan, as assistant superintendent of the new Ben Nevis weather station.

Bruce's acquaintance with the Arctic came through his friendship with Mill, who first recommended Bruce in June 1896 for the post of naturalist on the Jackson-Harmsworth expedition to Franz Josef Land. On this expedition, Bruce met Albert Armitage and Reginald Koettlitz, both of whom were later to participate in the British National Antarctic Expedition (1901–1904), and, to his amazement and delight, the Norwegian explorer Fridtjof Nansen. In 1898, Bruce sailed again as naturalist to the Arctic, this time with the industrialist Andrew Coats aboard his steam yacht *Blencathra,* bound for Novaya Zemlya. The ship returned to Tromsø, where Bruce met Prince Albert of Monaco aboard his fine oceanographic research vessel Princesse Alice. Bruce was invited to accompany the Prince to Spitsbergen waters and to spend the winter of 1898–1899 in Monaco continuing his work as naturalist.

On returning to England Bruce looked repeatedly to the Antarctic for further research; he was possibly the best-qualified polar scientist in Britain at the time. Accordingly, he applied to join Robert Falcon Scott's expedition aboard *Discovery,* but Clements Markham, who was recruiting for the expedition, delayed so long in his reply that Bruce decided to put together an expedition of his own, and to make it exclusively

Scottish. This became the Scottish National Antarctic Expedition, 1902–1904, and Bruce's prime claim to fame as a polar explorer. On leaving the South Orkneys he left behind a scientific station that has become the oldest to survive in the whole of Antarctica.

In 1901, Bruce married Jessie Mackenzie, daughter of Alexander of Tain Easter Ross, and their first child, Eillium Alastair, was born in April 1902, and a daughter, Sheila Mackenzie Bruce, in 1909. The family lived in Joppa, close to Edinburgh, where William Bruce could continue his professional life. He established the Scottish Oceanographical Laboratory in 1906, which housed his vast collection of polar exhibits, but he was forced to close it in 1919 due to a shortage of funds. In 1909, he initiated the Scottish Spitsbergen Syndicate as a mineral prospecting company, and he returned there for several summers, but without any economic mining taking place. By 1920, he was failing in health, and he died in Edinburgh on October 28, 1921. By his express wish, his ashes were carried to Antarctic waters and scattered outside the harbour of Grytviken, South Georgia.

Peter Speak

See also **British National Antarctic *(Discovery)* Expedition (1901–1904); *Challenger* Expedition (1872–1876); Dundee Whaling Expedition (1892–1893); Markham, Clements; Scottish National Antarctic Expedition (1902–1904); South Orkney Islands**

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BULGARIA: ANTARCTIC PROGRAM

Bulgaria started its polar activities in Antarctica in 1967–1969, when Bulgarian meteorologists took part in the XIII Soviet Antarctic Expedition. In the austral summer season of 1987–1988 six Bulgarian scientists participated in joint projects with the British Antarctic Survey and the Soviet Antarctic and Arctic Research Institute. This Bulgarian programme was aimed at gathering valuable experience both in carrying out scientific research and the organization of the logistics in Antarctica. During this Antarctic season a refuge was established on Livingston Island (South Shetland Islands) on a spot located on the northeast side of the South Bay.

In the period between 1993 and 2005, Bulgaria organized twelve successive Antarctic campaigns. A summer base named "St. Kliment Ohridski" was established to accommodate a staff of fifteen. The base is functioning thanks to the logistic support and valuable help of the Spanish Polar Institutions. The Bulgarian and Spanish polar researchers work in close collaboration.

Organization and Scientific Activities

The Bulgarian Antarctic Institute is the national operator of Bulgarian Antarctic activities. The Institute organizes annual Antarctic campaigns and operates the Bulgarian Antarctic base, St. Kliment Ohridski. The Bulgarian Government is represented on the Executive Council of the Institute by a Vice-Minister of Foreign Affairs. Antarctic activities are planned by the Executive Council on recommendation by the Scientific Board of the Institute. The National Antarctic Programme is guided and financed predominantly by the Ministry of Foreign Affairs and partly by the Ministry of Education and Science and the Ministry of Ecology and Waters. Bulgarian Antarctic activities are under the aegis of the President of the Republic of Bulgaria.

The scientific part of the programme is implemented by scientific teams, provided with contracts, approved by the Antarctic expert commission at the Ministry of Education and Science. The main scientific topics include earth sciences, such as geology, geophysics, physics, glaciology, geomorphology, meteorology, and cartography; life sciences, such as zoology, botany, and ecology; and human medicine. Research work is implemented by means of 3-year projects undertaken by university-based or academic scientists. Emphasis is given to a multidisciplinary approach towards understanding the patterns and processes in main polar natural systems and their evolution.

The activities under the biological research programme have focused on the study of the biological diversity of the main habitats on Livingston Island. A number of plant and animal species and their communities have been described. The diversity of protozoa, diatoms and other algae, soil nematodes, and freshwater and interstitial crustaceans has been studied. Eight new species for the flora and fauna of the world have already been described and more are being studied. Communities of diatom algae, protozoa, and nematode tropic groups have been studied and patterns of their distribution among Antarctic habitats have been described. Penguin genetics and molecular biology are also studied as a tool for addressing questions of their systematic adaptation. The results of the Bulgarian biological research programme are published in the Series "Bulgarian Antarctic Research—Life Sciences."

The further development of Bulgarian biological studies in the Antarctic will include investigations into the structure and functioning of Antarctic terrestrial ecosystems and environmental monitoring based on heavy metal content in lichens and penguin feathers. A special project will be started to study the role of solar ultraviolet light as the prime ecological factor in the formation of cell lethality and mutagenic and carcinogenic effects together with their different protecting mechanisms including DNA-repair systems, antioxidant enzymes, and related proteins.

The main objective of the geological research projects will be to explain the stratigraphy and tectonics of the Mesozoic turbidity successions and the petrology of the subductional plutons and to draw up a new model of tectonic–magmatic history of the South Shetland Islands. The first find of macrofossil, the age-diagnostic Upper Tithonian ammonite reported from the Miers Bluff Formation of the Bulgarian scientists, will change the ideas about the geological evolution of the South Shetland Islands and Antarctic Peninsula during the Mesozoic. The further development of the Bulgarian geological studies will include detailed geological mapping in a scale of 1:5000, paleontological searches for macrofossils and microfossils, and paleoenvironmental interpretations.

The main trends of the glaciological and meteorological studies are to design drills and equipment used in vertical and horizontal drilling; to investigate the microclimate phenomena related to complex orography, glaciers, and proximately the ocean; and to automate the meteorological monitoring in order to collect data, necessary for the glaciological and biological observations. Dating of the ice layers of the Hurd Peninsula glaciers and analysis of the elements and isotopes of ice samples are among the expected results.

Bulgarian Station St. Kliment Ohridski

The summer-only station St. Kliment Ochridski is located at 68°38′ S, 60°21′ W on a small saddle on Hurd Peninsula, 150 metres behind South Bay, Livingston Island. The Spanish station Juan Carlos I lies 1.7 km to the southwest. Opened in 1988, the station is administered by the Bulgarian Antarctic Institute and financed by the Ministry of Foreign Affairs.

The station's seven buildings are located on a ridge 20 m above the beach. The original station living hut of 3.5 x 6 m was built in 1988 and is steel-framed and clad in sandwich panel, providing great thermal efficiency. It is now used as the communications centre and also has overflow accommodation for five. Adjacent to this is a 2.5- x 4-m wooden-clad container used as a store for food, emergency equipment, and other supplies. Two portable arch-frame "Weatherhaven" shelters of 8 x 4 m and 4 x 2 m respectively house an inflatable rubber boat and associated gear, and provide potential extra accommodation. The main station building is of sandwich-panel construction clad with prefabricated concrete panels, and is approximately 12 x 5 m, with food storage in a rock-walled subfloor area. This building includes a sizeable kitchen/dining area, bathroom, clinic, and two bedrooms of four bunks apiece with some limited desk space. Power generators are housed in a steel-framed and metal-clad shelter of 4 x 6 m, to the south of the main building. A small A-frame shelter that serves as a chapel in summer and a snowmobile store in winter is located 300 m behind the station.

CHRISTO PIMPIREV

See also **Algae; Antarctic Peninsula; Arctic and Antarctic Research Institute, Russia; British Antarctic Survey; Nematodes; Penguins: Overview; Protozoa; Russia: Antarctic Program; South Shetland Islands; Spain: Antarctic Program**

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BYRD, RICHARD E.

Richard E. Byrd was the pivotal figure in the twentieth century for the United States in Antarctica. Byrd organized, led, or shared the leadership of five expeditions to Antarctica. Before his death in 1957, some even referred to Byrd as the "Mayor of Antarctica" because of his stature and influence over US efforts in the continent.

Early Life

Born in Winchester, Va., on October 25, 1888, Richard Evelyn Byrd traced his ancestral roots to one of the founding and prominent families in the state. His father and namesake was an attorney in

Winchester, served as a prosecuting attorney for 20 years, and became speaker of the house in the state assembly. The explorer's brother, Harry, added to the political luster of the family, first as governor and then as a United States senator. Access to prominent people in government and in society gave Byrd a significant advantage in his career as an explorer.

Byrd moved to a career as an explorer gradually. Travel interested him first. At the age of 12, he traveled alone around the world, after visiting a family associate in the Philippines. Opportunities to see the world and be a leader drew Byrd to a career in the US Navy. In 1908, he won an appointment to the United States Naval Academy in Annapolis, Md., from which he graduated in 1912.

As a junior officer in the Navy, Byrd had difficulty standing for long watches at sea, due to injuries in football and gymnastics, which had weakened his right foot. While serving on the USS *Wyoming,* he fell through an open hatch and reinjured his foot, forcing surgery and rehabilitation. After duty on the presidential yacht *Mayflower,* Byrd retired from active duty.

World War I restarted Byrd's career and turned his attention to aviation. Called to active duty, he ran the naval militia of Rhode Island in 1916. Having proven his leadership abilities, Byrd earned a transfer to Washington, D.C., first at the Bureau of Naval Personnel and then at the Commission on Training Camps in 1917. With the support of the secretary of the Commission, Byrd won an appointment as a naval aviation cadet at Pensacola Naval Air Station. After earning his wings, he continued as an instructor. Byrd's interest in airplanes focused on the navigational challenges of long-distance flight. He became expert in the use of the bubble sextant and wind-drift indicator as tools of aerial navigation. In 1917 he proposed to fly airplanes—flying boats—from Halifax, where he was stationed, to Europe rather than transport them on ships. In 1919, Byrd helped to plan the successful trans-Atlantic crossing by NC-4 flying boats.

Opportunities and accomplishments over Arctic ice and Atlantic water set the stage for Byrd's work in Antarctica. In 1925, Byrd had charge of the US Navy's flying boats on the private expedition to Greenland commanded by the veteran explorer Donald McMillan. That expedition was the first to use the Bumstead Sun Compass in aerial navigation and short-wave radio for communication. Unfortunately, the expedition did not have enough favorable weather for Byrd to try to fly across Greenland to the North Pole.

In 1926, Byrd's flight to the North Pole provided the accomplishment that launched his career in Antarctica. The well-connected Byrd asked financial support from Henry Ford, John D. Rockefeller, and others. In addition, he arranged well-paid contracts with news and film media. Finally, Byrd had enough money to buy a used but well-tested airplane—a three-engine Fokker that he named in honor of donor Edsel Ford's daughter Josephine. He leased a surplus ship, *Chantier,* to carry him, his plane, and his expedition members to Spitsbergen. There, Byrd faced Roald Amundsen, who had been planning an airship attempt. With help from Bernt Balchen, a member of Amundsen's expedition, Byrd as navigator, and pilot Floyd Bennett, whom Byrd had met in Pensacola, they took off before Amundsen. During the flight, the plane developed an oil leak but, according to Byrd, the two persevered until they reached the North Pole on May 9, 1926.

Critics of Byrd have doubted his accomplishment of the North Pole. They point to the duration of the flight and question that the plane had the speed to reach the objective in the time before he returned. Byrd's notebook of the flight contains erasures, still legible, that skeptics consider important. Nevertheless, Byrd's claim of the North Pole made him a national hero. The US Congress awarded him the Medal of Honor and promoted him to commander. New York City threw him a ticker-tape parade. A businessman and philanthropist, Henry Wanamaker, offered Byrd a plane and financial support to be the first to fly to France. In 1927, another ticker-tape parade followed when Byrd became the third after Charles Lindbergh to fly from the United States to Europe.

Byrd and Antarctica

Buoyed by his accomplishments, Byrd turned to the Antarctic as the theater of his ambitions. As he explained in his book *Skyward,* one of the principal reasons for going to Antarctica was to add to the knowledge of aviation by testing people and airplanes in hostile environments: "Spectacular flights accelerate progress, for when the flight is decided upon, the necessity in some cases produces inventions and developments which, in the ordinary course of events, would tend to be very slow and uncertain" (*Skyward* 297).

Byrd was an unusual explorer. Not an able skier, he excelled as a planner, organizer, and publicist. His expeditions to Antarctica were the largest of the time. Apart from the basic supplies of food, clothing, and shelter, each used airplanes, multiple ships, motorized transport, and radio equipment. Each included distinguished scientists and programs of investigation in such fields as meteorology, geology, and biology, which entailed added equipment and supplies.

Constant publicity helped to stoke public interest, raise enough money to pay the debts of one expedition, and sow the seeds of the next. Byrd gave much attention to publicists and to providing the news media with good stories. His first expeditions included professional writers and a film crew from Paramount. Byrd himself was photogenic, and each expedition offered drama as well as accomplishment. The most dramatic moment of the first expedition was the flight over the South Pole. In the second, during which the US Congress promoted him to Rear Admiral, Byrd almost died of carbon monoxide poisoning in an isolated hut during the winter.

His last three expeditions also applied modern technology to geographical exploration and scientific investigation, but they were different in funding and purpose. After returning from Antarctica in 1935, Byrd began raising money privately for another expedition. However, the financial depression in the United States had worsened and raising money privately proved too difficult. International tensions provided another opportunity for exploration in Antarctica. Concerned about the claims of other nations to Antarctica, President Franklin D. Roosevelt, whom Byrd had befriended years before, created an interagency task force, the United States Antarctic Service. Its purpose was to set up and keep two scientific bases in Antarctica. Leadership of the enterprise went to Byrd, who added the funds he had raised. Although Byrd organized the effort successfully, it ended prematurely in 1941 because of World War II.

Following the war, Byrd returned to Antarctica in 1947 during Operation High Jump. Byrd had the title of Officer-in-Charge and had leadership of the scientific program. However, Rear Admiral Richard Cruzen had command of the 4700 naval and marine personnel and 13 ships involved. It succeeded in mapping roughly 1.5 million square miles of Antarctica. The brief duration of High Jump, which did not winter in Antarctica, severely limited scientific work. An important purpose of the expedition was to test the equipment and expertise of the US Navy.

Byrd was not an active military officer or an official, but he continued to play an important role in the government-funded expeditions of the US in Antarctica. After efforts to lead another Operation High Jump failed, Byrd continued to push for further exploration and scientific investigation of Antarctica. When the United States decided to take part in the International Geophysical Year of 1957, Byrd became involved in the planning. In 1955, the 67-year-old Byrd received appointment, without salary, as Officer in Charge, US Antarctic Programs. He was to be "the senior US representative charged with effective monitorship over those political, scientific, legislative, and operational activities which comprise the total US Antarctic Program." Byrd's last visit to Antarctica in 1955 was to plan the bases necessary for the scientists. He died 2 years later on March 11, 1957.

Byrd's career in Antarctica left many legacies. Apart from places named by and for him, his expeditions are the basis of potential US claims to the continent. He also developed further the application of modern technologies to exploration in Antarctica. Although he was not the first to use airplanes, radios, or trucks in Antarctica, his expeditions proved their usefulness there. Finally, the scientists who accompanied Byrd not only made important discoveries but also educated and inspired generations of future scientists. They advanced knowledge of the Earth's ecological forces and worked to keep Antarctica a laboratory for science.

Raimund E. Goerler

See also **Amundsen, Roald; Aviation, History of; International Geophysical Year; Siple, Paul; United States Antarctic Service Expedition (1939–1941); United States (Byrd) Antarctic Expedition (1928–1930); United States (Byrd) Antarctic Expedition (1933–1935); United States Navy Developments Projects (1946–1948)**

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CAMPBELL ISLANDS

The Campbell Islands group, situated at latitude 52°33′30″ S, some 700 km south of the South Island of New Zealand, comprises the main Campbell Island (11,268 ha) and several islets, principally Dent Island (23 ha) and Jacquemart Island (19 ha). The islands are the dissected remnant of a Miocene shield volcano (6–11 million years old), rising to 569 m at Mt. Honey. Wave erosion has removed the volcano's western flank, leaving an unbroken line of cliffs. Pleistocene-age glaciers have carved cirques, U-shaped valleys, and fiords, the largest of which is Perseverance Harbour. Peat blankets the landscape and is prone to landsliding.

The climate is cool (mean annual temperature of 6°C), cloudy, windy, and wet (annual rainfall 1400 mm) with about 325 rain days during the year. Winter snowfall is usually light and transient.

There are 218 species of vascular plants. Grassland, mainly of *Poa litorosa* and *Chionochloa antarctica,* predominates. Following removal of sheep and cattle, there has been remarkable regrowth of megaherbs, including all three species of *Pleurophyllum—P. speciosum, P. criniferum,* and *P. hooker*—together with two large carrot relatives, *Anisotome latifolia* and *A. antipoda,* and the Macquarie Island cabbage, *Stilbocarpa polaris.* The unpalatable lily *Bulbinella rossii* forms extensive meadows. On moorland above 300 m are two endemic forget-me-nots, *Myosotis antarctica* and *M. capitata*. A gentian, *Gentiana antarctica,* and rosette daisy, *Damnamenia vernicosa,* occur, the former endemic to Campbell Island, the latter found also at the Auckland Islands. A coastal fringe of shrubland extends to about 180 m in altitude, with *Dracophyllum longifolium* and *D. scoparium* forming a dwarf forest about 3–5 m tall, and *Coprosma* and *Myrsine* also present. Some 81 species of introduced plants have been recorded, *Poa annua* being especially widespread.

The islands are a major global centre of albatross diversity, with six breeding species: the endemic Campbell Island *(Thalassarche impavida)* (26,000 pairs), grey-headed, black-browed, southern royal (14,000 pairs), Antipodean *(Diomedea antipodensis),* and light-mantled sooty albatross. The islands are the main breeding ground for the rare yellow-eyed penguin *(Megandyptes antipodes)* (500–600 pairs), while eastern rockhopper penguins *(Eudyptes chrysocome filholi)* are abundant but recently have reduced markedly in numbers to around 50,000 pairs. Several species of petrel breed, especially on predator-free islets, together with an estimated 1000 endemic Campbell Island shags *(Leucocarbo campbelli)*. Important among the land birds are the flightless Campbell Island teal *(Anas nesiotis),* one of the world's rarest ducks, which was rediscovered on Dent Island in 1975; the Campbell Island snipe (*Coenocorypha* undescribed sp), discovered on Jacquemart Island in 1997; and the New Zealand pipit *(Anthus novaeseelandiae)*.

The New Zealand (Hooker's) sea lion, New Zealand fur seal, and southern elephant seal breed in small numbers, and southern right whales congregate for mating. A massive poisoning campaign in 2001 may have eradicated the Norway rat and cats, the last of the introduced mammalian predators.

Campbell Island was discovered by sealers in 1806, and seals were decimated by the 1830s. Shore-based whaling continued until 1916. Sheep farming commenced in 1895 but terminated in 1931, with the last feral sheep eliminated in 1992. A wartime coast-watching station, occupied from 1941 to 1945, was subsequently used as a meteorological station, which was replaced in 1958 and closed in 1995. Sporadic scientific and conservation expeditions occur and small numbers of seaborne tourists visit each year under strict supervision. Campbell Island is a nature reserve and World Heritage site.

Paul Dingwall

See also **Albatrosses: Overview; Black-Browed Albatross; Grey-Headed Albatross; Light-Mantled Sooty Albatross; Penguins: Overview; Royal Albatross; Southern Elephant Seal; Southern Right Whale**

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CANADA: ANTARCTIC PROGRAM

Canadian participation in Antarctic research started when Hugh Blackwall Evans was a member of the Southern Cross expedition, the first to spend a winter on the Antarctic continent in 1899, and the involvement has continued for over a century. Canada adhered to the Antarctic Treaty as a nonconsultative party in 1988, and subsequently ratified the Convention on the Conservation of Antarctic Marine Living Resources, the Convention on the Conservation of Antarctic Seals and, in 2003, the Protocol on Environmental Protection to the Antarctic Treaty. Environment Canada administers the Canadian legislation that implements the Environmental Protocol.

Organization of a coordinated Canadian approach to Antarctic science started in the early 1990s after an initiative of the Canadian Polar Commission (CPC) (www.polarcom.gc.ca). As a result, Canada joined the Scientific Committee on Antarctic Research (SCAR) in 1994 with the CPC as the adhering body. Canada became a Full Member in 1998 and established the Canadian Committee for Antarctic Research (CCAR) as the national committee for SCAR. Canada is also a member of the Council of Managers of National Antarctic Programs (COMNAP) through Natural Resources Canada's Polar Continental Shelf Project (http://polar.nrcan.gc.ca).

Canada does not have, nor does it plan to establish, an Antarctic base of its own, but seeks instead to use available space at existing facilities. This is aimed at reducing both cost and environmental impacts and recognizes that new satellite and remote sensing technology, increases in sample and data sharing and computer modelling projects make field programs less important than in the past.

A number of Canadian scientists, mainly faculty members from universities, and scientists from government laboratories participate in Antarctic research (see *Canadians in Antarctic research 2002–2004,* www.polarcom.gc.ca/antarctic/documents). The report also lists the contributions to Antarctic science they made during the same period. Canada does not have a separately funded and managed national Antarctic program as many other nations, but efforts are underway (as of fall 2004) to establish a Canadian Antarctic Research Program. In the meantime, the scientific effort is loosely coordinated through CCAR as the national committee for SCAR.

Research funding comes mainly from the granting councils (e.g., the Natural Science and Engineering Research Council [NSERC] and the Social Sciences and Humanities Research Council [SSHRC]) for university faculty and students and from government departments (for government scientists). Polar Continental Shelf Project operates the Canadian Arctic/Antarctic Exchange Program that promotes scientific exchanges between Canadian scientists and their Antarctic colleagues (http://polar.nrcan.gc.ca/pcs_whatwedo/index_e.aspx?ArticleID=657).

Based largely on experiences gained in Arctic Canada, a variety of Canadian companies provide goods and services to Antarctic operations of many nations. Examples are air services (e.g., by Kenn Borek Ltd.), prefabricated buildings, camping equipment and cold weather clothing. The Canadian RADARSAT satellite provided imagery for the construction of a detailed mosaic map of the continent. Since the early 1990s Canadian tour companies have regularly organized ship-based tours to the Antarctic Peninsula area.

Olav H. Loken

See also **Antarctic Peninsula; Antarctic Treaty System; British Antarctic *(Southern Cross)* Expedition (1898–1900); Convention on the Conservation of Antarctic**

Seals (CCAS); Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Protocol on Environmental Protection to the Antarctic Treaty; Tourism

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CAPE PETREL

The Cape petrel (*Daption capense,* a member of the family Procellariidae, order Procellariiformes) is a widely distributed petrel of the Southern Ocean. It is a member of the fulmarine petrel complex, which also includes Antarctic petrels, snow petrels, northern and southern giant petrels, and northern and southern fulmars.

The name of the genus *Daption* is actually an anagram of *pintado,* the Spanish word for "painted," a description first ascribed to the bird by early sailors in the Southern Hemisphere. The species is named after the locality where it was first described, the Cape of Good Hope. It is still occasionally called Cape pigeon, a reference to the bird's stocky build and habit of seizing individual food items like a pigeon pecking at grain. In Spanish, it is known as *petrel moteado,* meaning "spotted petrel."

Cape petrels have a distinctive appearance, with their strikingly checkered and mottled black and white upperparts and black head, bill, and feet, contrasting strongly with primarily white underparts. Males and females do not differ in plumage, although males are slightly larger in size (males weigh approximately 470 g and females approximately 445 g).

Cape petrels are loosely colonial breeders with a wide, circumpolar distribution. There are two recognized subspecies, *D. capense capense* and *D. capense australe*. The considerably more abundant nominate subspecies, *D. capense capense,* is concentrated in the Scotia Sea and sub-Antarctic, although it also breeds in the high Antarctic on peri-Antarctic islands. *D. capense australe* has a small population restricted to the sub-Antarctic islands south of New Zealand. Colony size ranges from a few scattered pairs to thousands of pairs.

The world population is considered stable and secure, with a crude global estimate of approximately one million birds. Due to its large global population, broad distribution, and generally remote and inaccessible breeding colonies, there are few conservation concerns for the species.

The timing of the breeding season events is consistent from one season to the next. Arrival at the colonies typically begins in mid to late October and is followed by egg laying in late November to early December. Chicks hatch in early to mid-January with fledglings departing at the end of February to early March. Like all procellariiform seabirds, Cape petrels are obligate single egg layers. Thus, they cannot lay a replacement if the original egg is lost. Cape petrels are considered annual breeders, although in certain years high numbers of birds forgo breeding, presumably due to poor body condition of prospective breeders.

Cape petrels nest in a variety of open habitat types, from flat and sloping ground to cliff ledges. Nests are either bare with collections of small stones, or shallow scrapes where soil substrate is available. Individuals tend to return to the same nest site year after year to breed with the same mate. The species is highly monogamous, with approximately 75%–85% of individuals breeding with the same mate as the previous year. Birds change mates because of a series of breeding failures in previous years or loss or delayed arrival of their mate. Cape petrels, like other petrels, are strongly philopatric, meaning that young birds typically return to their natal (birth) colony or one nearby to establish a nest and begin breeding.

There is little variation in laying date among years, and the timing of breeding is generally highly synchronized, presumably due to the limited window of opportunity for breeding (discussed later). Both parents share incubation duties and the care and feeding of the nestling. At the nest, both adults and nestlings employ an effective defense mechanism: they are accurate marksmen that can spit stomach oil up to 2 m away to dissuade potential predators, principally skuas *Catharacta* spp.

Procellariiform seabirds typically grow considerably more slowly than predicted for other birds of the same size. Interestingly, the fulmarine petrels, including Cape petrels, exhibit a compressed breeding season relative to other birds in the order, meaning that both their incubation and nestling periods are shorter (approximately 50% shorter than predicted). It is believed that this pattern is an adaptation for breeding in the short, high-latitude summers where there is limited time in which food is highly abundant and environmental conditions are appropriate for breeding. Although chicks grow twice as fast as predicted, their general pattern of growth is similar to that of other petrels; chicks typically reach a peak mass that may exceed 150% of adult mass, followed by mass recession until fledging.

Survival rates are lowest for fledglings but subsequently increase for birds that survive their first year of life. The few estimates of adult survival that exist for this species suggest that annual adult mortality rates are approximately 5%, resulting in a life expectancy of over 20 years. Age at first breeding is variable but averages 6 years.

Like other petrels, Cape petrels are opportunistic foragers. Their diet consists primarily of euphausiids (krill), fish, squid, and carrion, especially seal and whale carcasses. During the breeding season, krill frequently dominate the diet; in the Antarctic, numbers of Cape petrels at sea are positively related to krill density. Cape petrels employ a variety of surface feeding techniques to capture prey, including surface seizing and scavenging. Occasionally, Cape petrels make shallow surface dives to approximately 1 m to pursue prey items. Cape petrels are also habitual ship followers, foraging on discarded scraps and offal in addition to prey items carried to the surface by propellers. Evidence suggests that Cape petrels may use their well-developed olfactory abilities to help locate food patches. Foraging trips during the chick-rearing period usually range from 2 to 5 days in length.

When breeding, birds are restricted to foraging in the surrounding inshore and shelf waters within a few hundred kilometers of colonies. Outside of the breeding season, birds are highly dispersive, spending most of their life on the open ocean.

At the conclusion of the breeding season in late February and early March, Cape petrels begin to migrate northward. This migration is extensive, frequently extending up to 15°–20° S. Along the west coast of South America, high numbers of Cape petrels range up the Humboldt Current to the subtropics and occasionally as far as the tropics, with vagrants rarely reaching the Northern Hemisphere.

Peter Hodum

See also **Albatross and Petrels, Agreement for the Conservation of; Antarctic Petrel; Birds: Diving Physiology; Fish: Overview; Northern Giant Petrel; Petrels (Pterodroma and Procellaria); Seabird Conservation; Seabird Populations and Trends; Seabirds at Sea; Snow Petrel; Southern Fulmar; Southern Giant Petrel; Squid; Zooplankton and Krill**

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CARBON CYCLE

The carbon cycle is defined as the flow of carbon through the atmosphere, the ocean, organisms and organic sediments and sedimentary rock. As in all seas, the marine carbon cycle in the Southern Ocean is regulated by (1) the transfer efficiency of carbon dioxide (CO_2) between atmosphere and the ocean, (2) the solubility (thermodynamic) pump, and (3) the biological pump. A fourth pump, the carbonate (alkalinity) pump, is presumably of restricted importance south of the Polar Front due to the scarcity of calcifying organisms. There is particular interest at present in understanding the sinks where CO_2 is sequestered and how long it remains there.

Like other gases, CO_2 flows from high to low partial pressure (p). Whereas mean pCO_2 in the atmosphere has increased from ~360 to ~380 ppm in the past 40 years, it ranges from 150–200 ppm in the surface layer of polar seas to 500–550 ppm in the surface layer of tropical seas. This is a consequence of strong biological pumping and upwelling of CO_2-rich water. Generally, the concentration of CO_2 is higher in deep water than near the surface. Because of the comparatively small variation in atmospheric pCO_2, exchange of CO_2 between the atmosphere and the ocean is almost entirely caused by the pCO_2 variation in the surface ocean on decadal time scales.

Because the transfer efficiency of CO_2 (and gases in general) between the atmosphere and the ocean not only is proportional to the magnitude of the gradient and but also critically dependent on strong wind, the exchange of CO_2 between the atmosphere and the ocean along the roaring forties north and south of the Polar Front is presumably efficient. Realistic modeling of the wind-dependent transfer of CO_2, however, is paramount because otherwise predictions of the size of carbon sinks and sources can easily err by a factor of 1.5–2.

Present estimates indicate that the Southern Ocean is the primary sink for anthropogenic CO_2 (CO_2 supplied on top of a calculated flux of nonanthropogenic CO_2), amounting to ~2 petagrams (1 Pg = 1 gigaton) of carbon per year, which is a little above a quarter of the global anthropogenic supply. Because of small convection depth (<1000 m), however, the anthropogenic CO_2 is not stored in the deep Southern Ocean. Instead it is transported northwards towards the tropical seas with

Antarctic Intermediate Water that is formed near the Polar Front. The concentration of anthropogenic CO_2 in the Southern Ocean is the lowest in any ocean, <20 mol m^{-2} as opposed to 30–50 mol m^{-2} between 30° and 50° S and >50 mol m^{-2} in the North Atlantic.

The solubility carbon pump is based on the fact that cold water can hold more of free CO_2 in solution than warm water at the same partial pressure, ~4% more per centigrade of temperature decrease. The solubility pump is therefore most important in surface currents that are cooled while flowing polewards. The sequestration of CO_2 in the Southern Hemisphere therefore takes place mainly between the tropics and the Polar Front. The area south of the Polar Front is characterized by upwelling of cold North Atlantic Deep Water and, near the Antarctic continent, by formation of bottom water. These water types do not warm or cool significantly while moving vertically. With almost no biological activity in the winter, large stretches of the Southern Ocean are likely to be neutral or, perhaps, a weak CO_2 source.

The biological carbon pump is based on sequestration of CO_2 by photosynthetic plankton (phytoplankton). This lowers pCO_2 in the euphotic (well lit) zone and therefore increases the gradient in pCO_2. Given strong wind, this promotes draw-down of CO_2 or weakening of outgassing from the ocean.

A large part of the carbon sequestered by photosynthesis is grazed and broken down by oxic respiration in a matter of days by heterotrophic plankton, including microbial heterotrophs within the euphotic zone. This returns sequestered CO_2 to the water. The remaining part sinks (export production) and is subject to the same breakdown processes. Less than 3% of the sinking particulate matter will reach the seabed of the deep ocean (>3500 m depth) and take part in the formation of sediments. CO_2 arising from respiration in the upper 1000 m of the water column is likely to reach the upper ocean within a year or less.

Biological carbon pumping is to a great extent regulated by the same factors that regulate primary production; that is, presence/absence of sea ice, vertical mixing, grazing and the availability of micronutrients and macronutrients. A phytoplankton bloom in Antarctic waters typically represents 10–25 mmol m^{-3} of particulate organic carbon (POC), yet higher values can be observed in the marginal ice zone. Enhanced phytoplankton biomass is also typical around islands. The predominant phytoplankton are diatoms and the prymnesiophyte *Phaeocystis antarctica,* of which aggregates of the latter sink particularly rapidly. *P. antarctica* seems to be prominent in the Ross Sea, where it is competitive when the depth of mixing is 80–100 m; diatoms seem to be favoured by stratified water. At present the knowledge of growth strategies of different phytoplankton is very limited due to a lack of experimental research.

Following the phytoplankton blooms near the Polar Front and in the marginal ice zone, vast stretches of the surface water of the deep Southern Ocean enters a high-nitrogen, low-chlorophyll (HNLC) state. This state is characterized by strong iron and grazing control of the growth rate and the phytoplankton biomass, respectively, as verified by several field experiments since the early 1990s. This and limitation by light leave about half of the macronutrients in the water after the blooms have concluded. Iron is needed for nitrate uptake and in the electron transport chain of mitochondria, and therefore lack of iron retards nitrate and carbon uptake. Silicate uptake in diatoms, however, is not affected, and therefore iron-deficient diatoms can be heavily silicified, which in turn leads to rapid sinking. This may explain why bottom sediments in the low-productive HNLC regions are abnormally rich in diatomaceous silicate ("opal").

Estimates of the annual primary production in the Southern Ocean are uncertain and ranges from 1.0 to 3.6 Pg C (average, 2.3 Pg C), which corresponds to 28–100 g C m^{-2} (average, 65). This is a little higher than the regional uptake of anthropogenic carbon. The bulk of the annual primary production, 0.78–3.2 g C, takes place in the permanently open water, mainly the Polar Front zone. The marginal ice zone contributes 0.14–0.38 Pg C and the ice-covered zone, 0.036 Pg carbon. The total annual primary production south of the Polar Front corresponds to 26–90 g C m^{-2}, clearly lower than the average for the global ocean, ~110 g C m^{-2}.

Annual export production of POC south of 50° S is ~1 Pg C (~10% of the global export production) and between 30° and 50° S, the sub-Antarctic zone, ~2 Pg C. The highest vertical carbon flux south of 50° S, 30 g C m^{-2}, is observed in the Polar Front zone, and the lowest, 5–10 g C m^{-2}, is in the ice-covered parts of the Ross and Weddell Seas. The distribution of export production is therefore closely related to the distribution of primary production. Export of dissolved organic carbon (DOC; actually soluble and semisoluble) in the upper 100 m is ~0.4 Pg C, decreasing to ~0.1 Pg C at 500 m depth and <0.1 Pg C at >3500 m depth, corresponding to 40%–50% of the vertical POC flux.

The vast area of HNLC waters in the Southern Ocean has suggested the idea of enhancing biological carbon pumping by fertilizing these waters with iron. To succeed, such fertilization should generate blooms of fast-sinking diatoms, which have high iron requirements. The C:Fe ratio of such diatoms is <850 (w/w). Sequestering 1 Pg of carbon, about one-eighth of the annual anthropogenic carbon supply, would therefore require dumping of >0.0032 Pg of iron II sulfate into the HNLC-regions of the Southern Ocean (~32 thousand 10,000-ton shiploads) during the course of 3–4 months. To ensure that 1 Pg of carbon reaches deeper than 1000 m, the project had to be sized for sequestration of 10 Pg carbon. Worse, if coccolithophorid blooms arise, calcification, which produces CO_2 can neutralize the photosynthetic sequestration of CO_2. In any case, sequestering 10 Pg of carbon by means of iron fertilization is likely to sequester ~1.8 Pg of nitrate-nitrogen, which is about half of the nitrate pool in the upper 500 m of the HNLC regions of the Southern Ocean, and a similar amount of silicate. Thus, the same amount will be lost from the nutrient transport with Antarctic Intermediate Water towards the tropical zone. As a consequence, marine bioproduction and carbon pumping in the tropical zone would decrease strongly, yielding a net change in global carbon pumping close to zero. And the ecological consequences of the gross redistribution of bioproduction from the tropical zone to the Southern Ocean would be enormous.

Recent models of the carbon cycle in the Southern Ocean south of the Polar Front indicate annual sequestration of ~0.47 Pg C, with interannual variability ±0.2 Pg C, largely related to the El Niño Southern Oscillation-linked Antarctic Circumpolar Wave. Future increase in atmospheric CO_2 may strengthen the role of the Southern Ocean as a carbon sink; on the other hand, this may be counteracted by stratification of the upper 500 m if the temperature of the upper Southern Ocean increases.

EGIL SAKSHAUG

See also **Antarctic Intermediate Water; Circumpolar Current, Antarctic; Marginal Ice Zone; Phytoplankton; Polar Front; Ross Sea, Oceanography of; Southern Ocean**

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CARTOGRAPHY AND CHARTING

Mapping Antarctica is especially challenging: It is remote and permanently covered in ice, and its hostile terrain and polar climate hamper the collection of data. Because it is also a dynamic continent, with glaciers advancing or retreating and huge icebergs (up to 95 miles in length) calving from ice shelves, maps need to be revised regularly.

For early cartographers, the size and shape of the continent were mere speculation. Depicted on a world map of 1531 as a hypothetical southern continent (Terra Australis), which extended as far north as Tierra del Fuego, its true extent was gradually revealed by exploration over the ensuing four centuries. Its known limits were reduced when several of the sub-Antarctic islands were first sighted, probably during the seventeenth century (e.g., Île Amsterdam in 1623, South Georgia in 1675), and when the Antarctic Circle was crossed by James Cook in 1773. Subsequent ship-borne exploration, mostly searching for new sealing and whaling grounds, led to the discovery of the South Shetland Islands in 1819 and Antarctica in 1820. Seasonal and permanent floating ice around Antarctica hindered access by ship and it was the twentieth century before extensive inland travel began, with Robert Scott's first expedition of 1901. The first systematic aerial photography was acquired in 1928–1929 by the Wilkins-Hearst Antarctic Expedition, and by the 1960s most of Antarctica's coast and hinterland had been visited or photographed from the air. However, the launch of the US Landsat satellites in the 1970s had the most significant influence on Antarctic cartography, providing an accurate overview of large parts of the continent for the first time.

Although charts were prepared by the early explorers, many in-shore waters were still poorly charted, even uncharted, in the late 1940s when systematic surveys, using echo-sounders, began. On land, several national mapping agencies had published reconnaissance maps by the 1950s but, after the International Geophysical Year (IGY; 1957–1958), Geographic Location and Number of Maps and Data, at Different Scales, Used to Prepare the SCAR Antarctic Digital Database*

Scale	Country of origin	Geographic location	Number
1:200,000	Russia	Marie Byrd Land	2
	UK	Theron Mountains, Coats Land	2
1:250,000	Australia	Bunger Hills, East Antarctica	1
	Japan	Eastern Dronning Maud Land	2
	Norway	Western Dronning Maud Land	32
	UK	Antarctic Peninsula, South Shetland Islands, parts of Ellsworth Land and Coats Land	54
	USA	Parts of Ellsworth Land, Marie Byrd Land and the Transantarctic Mountains	78
1:400,000	Germany	Coastal sections of Coats Land and western Neuschwabenland, derived from geocoded satellite images	Digital data
1:500,000	USA	Parts of Ellsworth Land and Marie Byrd Land	3
1:1,000,000	Australia	Coast of East Antarctica (Enderby Land to Oates Land)	22
	Russia	Mostly high-latitude West Antarctica	13
	USA	Ross Ice Shelf	2
1:1,500,000	Argentina	Part of Larsen Ice Shelf	1
1:2,000,000	Japan	Eastern Dronning Maud Land	1
	Germany	Filchner and Ronne ice shelves	1
1:3,000,000	UK	Part of interior of continent	2
1:5,000,000	USA	Ronne Ice Shelf	1

*Versions 1.0–3.0. Additions released as Version 4.0 were derived from digital data only and are not recorded here.

increased scientific activity required more accurate maps and charts. Australia, Japan, New Zealand, Norway, Russia, the United Kingdom (UK), and the United States (US) undertook systematic mapping for their scientific programs; all, except Russia and the US, limited map production to specific sectors, representing their territorial claims. Other countries (e.g., China, Germany, Poland, and Spain) mapped only their research areas and scientific stations. Through the Scientific Committee on Antarctic Research (SCAR), international agreement was reached in 1961 on standard symbols, projections, and scales to use on Antarctic maps, and to avoid duplication of effort by freely exchanging information. Mapping sub-Antarctic islands is the responsibility of their claimant nation.

Initially, Antarctica's hostile environment and lack of exposed rock for establishing ground control (only 0.33% of its surface is exposed rock) made systematic surveys difficult to achieve. In 1943, the British began making local surveys from scientific stations, with an astrofix as origin, using triangulation/trilateration techniques supported by exploratory sledge-wheel and compass traverses (a bicycle wheel with cyclometer towed behind a dog-sledge measured distances and a prismatic compass gave azimuth and bearings). When reconnaissance surveying ended in the Antarctic Peninsula in the 1970s, electromagnetic distance measuring devices were being used and a US/UK control network of Doppler satellite positions had been established. Vertical aerial photography of northern Antarctic Peninsula, acquired by the Falkland Islands and Dependencies Aerial Survey Expedition, 1955–1957, contributed to the British mapping program.

The US produced reconnaissance maps of East Antarctica in 1947 and in 1959 began publishing 1:250,000 scale maps of the Transantarctic Mountains and parts of West Antarctica. Those maps and a series of 1:500,000 scale hill-shaded sketch maps, begun in 1963, were compiled from ground survey and tri-camera aerial photography (three cameras, operated simultaneously, with one vertical and two pointing obliquely sideways). After IGY, Australia mapped much of the East Antarctic coast at 1:1,000,000, revising its maps using Russian space photography from the Kosmos satellite, launched in 1966. Russia produced 1:1,000,000 maps of the Antarctic coast and areas of rock outcrop, and other maps at a range of scales, including an Antarctic atlas, published in 1966.

In spite of the huge effort expended on data collection, insufficient ground control hampered the preparation of conventional maps, even at 1:250,000 scale, and, in the mid-1970s, satellite image maps became standard. Map coverage was still poor in

1989 when the UK initiated a project to digitize Antarctic maps; this became the international Antarctic Digital Database (ADD) under SCAR in 1990. The ADD is a seamless digital map prepared from sources at a range of scales, the largest scale with significant coverage (20%) of the continent being 1:250,000 maps of coastal regions, mountainous areas, and large areas of exposed rock (e.g., Transantarctic Mountains); smaller-scale maps were used to complete the database. The ADD was published on CD-ROM in 1993 and new versions have been released on the Internet since 1998.

Global positioning system satellites (GPS) were launched in the late 1980s and, for the first time, ground control could be achieved in Antarctica without people needing to remain on station, in uncomfortable conditions, for long periods. SCAR organized several international GPS campaigns in Antarctica, providing accurate geographic coordinates for a network of sites. Nations also undertook local GPS surveys to improve control for their modern mapping programs (e.g., producing large-scale maps 1:1000–1:50,000 of areas of special significance, such as scientific stations). A number of cooperative mapping programs developed in the 1990s through international agreements.

Higher-resolution satellite imagery (better than 10 m on the ground), and the use of digital cameras linked to GPS systems for aerial photography, have improved the quality and coverage of Antarctic maps. Digital cartography and Geographic Information Systems (GIS) now underpin many logistic and scientific programs in the Antarctic, including geological and thematic mapping, and coastal-change studies. The primary geographic source for continent-wide GIS applications is the ADD, a composite of information obtained over several decades. In 1997, the Canadian–US Radarsat Antarctic Mapping Mission acquired imagery of the entire continent within a month and produced the first high-resolution image mosaic of Antarctica in near real-time—the true shape of Antarctica's coastline was finally revealed at the end of the twentieth century.

Janet W. Thomson

See also **Amsterdam Island (Île Amsterdam); British National Antarctic *(Discovery)* Expedition (1901–1904); Cook, James; Falkland Islands and Dependencies Aerial Survey Expedition (FIDASE) (1955–1957); Icebergs; International Geophysical Year; Place Names; RADARSAT Antarctic Mapping Project; Scientific Committee on Antarctic Research (SCAR); Scott, Robert Falcon; South Georgia; South Shetland Islands; Wilkins, Hubert**

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CETACEANS, SMALL: OVERVIEW

The diversity of small cetaceans in the Antarctic is low relative to temperate and tropical regions. The dolphin family, Delphinidae, is represented by three species—hourglass dolphin *(Lagenorhynchus cruciger),* long-finned pilot whale *(Globicephala melas),* and killer whale *(Orcinus orca)*. Only one species of porpoise (family Phocoenidae)—the spectacled porpoise *(Phocoena dioptrica)*—is found in the Antarctic. Four additional delphiniid species—southern right whale dolphin *(Lissodelphis peronii),* dusky dolphin *(Lagenorhychus obscurus),* Peale's dolphin *(Lagenorhychus australis),* and Commerson's dolphin *(Cephalorhynchus commersonii)*—are normally found in sub-Antarctic waters but occasionally enter Antarctic waters.

A physical barrier for most dolphins and porpoises moving into the Antarctic is the Polar Front. The hourglass dolphin and spectacled porpoise are the small cetaceans that regularly inhabit the Antarctic zone south of the Polar Front. The larger delphinids include the killer whale and the pilot whale and both occur north and south of the Polar Front. The killer whale is the only delphinid that occurs in the pack ice.

Other dolphin species spend time in sub-Antarctic waters close to the Polar Front and cross it intermittently. Of these, the southern right whale dolphin is pelagic and has a circumpolar distribution. The dusky dolphin, Peale's dolphin, and Commerson's dolphin are all found closer to shore in varying degrees, near the southern continents and around sub-Antarctic islands.

Most small cetaceans in the Antarctic and sub-Antarctic zones feed relatively near the surface (within 200 m) on a variety of fish, squid, and crustaceans. An exception is the long-finned pilot whale, which feeds predominately in deeper waters on squid.

Unlike many of the larger cetacean species, small cetaceans were not subject to whaling in the eighteenth and nineteenth centuries. In current times, small cetaceans inhabiting coastal waters are susceptible as bycatch in fishing nets. Localized, directed takes of dusky dolphin, Peale's dolphin, and southern right whale dolphin have been reported. Generally, the conservation status of small cetaceans in the Antarctic and sub-Antarctic are not known.

Hourglass Dolphin

This small, robust dolphin is boldly patterned with a white hourglass pattern on its side set against a black body. The large dorsal fin has a flattened-hook appearance in adult males. The hourglass dolphin is a fast, splashy swimmer. The average group size is 4–7 dolphins. They are often seen in association with fin whales or other large baleen whales, and feeding in large aggregations of seabirds.

The hourglass dolphin has a circumpolar distribution, in pelagic waters and around oceanic islands situated near the Polar Front. A circumpolar population estimate of 140,000 was based on surveys south of the Polar Front. The population likely exceeds this estimate since the dolphin's range extends to 45° S.

Long-Finned Pilot Whale

There are two species of pilot whales, long-finned and short-finned, but only the long-finned are found in the Antarctic region. Long-finned pilot whales in the Antarctic are accorded subspecies status, *G. m. edwardii.*

The long-finned pilot whale has a long and robust body with a prominent, bulbous melon. It is almost entirely black. It is a sexually dimorphic species: The males are longer and have an extremely large and broad-based dorsal fin. Pilot whales have a matrilineal social structure similar to that of killer whales. Groups typically consist of 20–90 whales. They are gregarious and are often observed in mixed species assemblages with hourglass or southern right whale dolphins. Pilot whales are deep-divers (500–600 m) that feed on squid and occasionally fish.

The long-finned pilot whale has a circumpolar distribution and is most frequently sighted near the Polar Front. It is common around Chatham Island where there have been mass strandings. A population of 200,000 has been estimated for whales south of the Polar Front.

Spectacled Porpoise

The spectacled porpoise is small with a distinctive color pattern. The upper body is black and sharply demarcated on the longitudinal axis from the white lower body. This species is sexually dimorphic: Adult males have a much larger dorsal fin than adult females. The common name refers to a contrasting black and white eye ring visible in most adults. Spectacled porpoises are usually observed slow-rolling at the surface, and they are shy around vessels. Most groups are small, consisting of 1–3 individuals.

Sightings of spectacled porpoise are rare but widely distributed, indicating a possible circumpolar distribution. They are found in the open ocean as well as around sub-Antarctic islands. They are difficult to observe at sea except in good weather, so they may be more common than sightings would indicate. There is no population estimate for this species.

Southern Right Whale Dolphin

The southern right whale dolphin is one of an antitropical species pair: It has a close relative in the North Pacific, the northern right whale dolphin *(Lissodelphis borealis)*. The southern right whale dolphin is long and slender and possesses a striking black and white color pattern. The most notable aspect of its external morphology, however, is the complete absence of a dorsal fin. The southern right whale dolphin is a fast swimmer, often porpoising high out of the water. Group size ranges in the hundreds, sometimes as many as a thousand. It is frequently seen in association with other species such as the long-finned pilot whale and dusky dolphin.

The southern right whale dolphin most commonly inhabits deep water in the sub-Antarctic zone. It is also seen around Chatham Island and the Falkland Islands. There is no population estimate for this species.

Dusky Dolphin and Peale's Dolphin

These robust dolphins are similar in appearance, with complex color patterns of black, grey, and white, and a prominent dorsal fin. The dusky dolphin has the broader range of the two species, with an irregular distribution in continental shelf waters and around sub-Antarctic islands. It is acrobatic and gregarious, and commonly seen in groups of one hundred or more. Peale's dolphin, by contrast, usually occurs in small groups of two to seven. Its distribution is associated with kelp beds and with fast-flowing channel waters.

Commerson's Dolphin

The Commerson's dolphin is one of four species in the genus Cephalorhynchus that all have localized distributions in southerly, coastal waters. The Commerson's dolphin is the most wide-ranging species in this category. It is frequently sighted at sea by those departing on ships from South America to Antarctica.

PAULA A. OLSON

See also **Antarctic: Definitions and Boundaries; Killer Whale; Polar Front; Southern Ocean**

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CHALLENGER EXPEDITION (1872–1876)

Although in scale it was reminiscent of the great voyages of circumnavigation of an earlier era, the *Challenger* expedition was designed not to discover new lands but to explore the depths of the sea. This was a relatively new area of scientific research—now known as oceanography—that had developed rapidly during the previous quarter century. Voyages of discovery between 1750 and 1850 had made great progress both in exploring and in the scientific study of hitherto unexplored portions of the globe, but limitations in the resources available to them meant that in some respects they were only partially successful. One such area was the scientific study of the sea, and another the geographical exploration of the polar regions, but by the 1870s new ideas and technologies encouraged new approaches. Although the main objectives of HMS *Challenger*'s voyage of 1872–1876 were scientific, her officers were experienced naval surveyors, and among its subsidiary aims was an exploratory southern detour during the passage between the Cape of Good Hope and Australia. After visiting Îles Kerguelen, the *Challenger* crossed the Antarctic Circle early in 1874. Heavy pack ice prevented a landfall but the expedition spent a fortnight in high southern latitudes.

The *Challenger* was the first British naval vessel to visit Antarctic waters since Sir James Clark Ross's expedition in the 1840s. As well as magnetic observations, Ross had also carried out pioneering oceanographic research. However, the procedures involved were still at an early stage of development and errors in his painstaking observations reduced their usefulness. By the 1870s, huge strides had been made in the theory and techniques of deep-sea observation.

The *Challenger* expedition originated from an initiative by two British biologists, William Benjamin Carpenter and Charles Wyville Thomson. They realized that experience gained by surveyors during two decades of laying submarine telegraph cables, together with the introduction of steam power, had opened up new opportunities for deep-sea investigation. On dredging cruises made in HMSS *Lightning* and *Porcupine* between 1868 and 1870, they discovered living creatures well below the supposed 300 fathoms limit of life. On the basis of the associated sea-temperature observations, Carpenter also proposed the existence of a general oceanic circulation governed by density differences. When his ideas met with a critical reception in some quarters he proposed a grand voyage of oceanic discovery to sample the life of the deep sea on a wider scale, and also to collect data supporting his theory.

Carpenter was successful in winning public as well as scientific support for this enterprise, and the *Challenger,* a steam-assisted screw corvette, sailed in December 1872. Its captain was George Strong Nares, a veteran of the Franklin searches of the 1850s, and Thomson headed a team of civilian scientists. After a year working in the Atlantic, the vessel arrived at Cape Town late in 1873. The scientific programme involved routines of deep sounding and dredging, together with observations of the physical and chemical properties of sea water, but other work was also undertaken, and during the next leg of the cruise Nares had orders to head into the Southern Ocean and if possible locate land sighted by the American expedition under Lieutenant Charles Wilkes in 1840.

After visiting the Prince Edward Islands and sighting Îles Crozets, where adverse weather conditions prevented landing, *Challenger* reached Kerguelen in early January 1874 and spent three weeks completing the survey of the island. Continuing south, they visited Heard Island, which with Îles Crozets was being considered as base for a Transit of Venus expedition later that year (which ultimately went to Kerguelen). On February 16, 1874, *Challenger* became the first steam vessel to cross the Antarctic Circle before encountering pack ice in latitude 66°40′ S, longitude 78° E. The weather being fine, Nares skirted the pack eastwards, in the hope of sighting Wilkes' Termination Land. However on February 24, conditions deteriorated and after sustaining minor damage in collision with an iceberg *Challenger* turned north, towards Australasia and the Pacific.

Although *Challenger* spent a relatively short time in Antarctic waters and never sighted the continent, the expedition contributed to the renewal of interest in Antarctic exploration and provided valuable new scientific information about the area. The scientists and surveyors added to knowledge of sub-Antarctic islands and Antarctic sea ice and meteorology and pioneered modern oceanographic investigation of the region. John Murray found that "diatom ooze," the seafloor sediment prevailing in high southern latitudes, consisted principally of the microscopic skeletal remains of single-celled algae inhabiting the surface waters of the region. At this point in the voyage, *Challenger* was equipped only with maximum and minimum thermometers so that a temperature inversion in the surface layers, where cold but fresh melt water had accumulated, prevented bottom-water measurements but the fine weather experienced near the ice edge enabled the chemist J. Y. Buchanan to make valuable observations of the properties of seawater and sea ice. Trawling yielded in excess of 400 living species in southern waters, most of them new to science, while deep-sea soundings gave the first reliable indications of oceanic depths along the vessel's track, including one of 1300 fathoms (approximately 3000 metres) only a few miles from the land reported by Wilkes. Dredging operations also brought up pieces of rock from the sea bed, some of which were not of basalt, like the oceanic islands but granite and other rock types typical of a continental landmass. It was assumed that these had been deposited by icebergs and that their presence, together with that of large tabular bergs, was evidence that land with a covering ice sheet, similar to that discovered by Ross on the far side of the Pole, lay farther to the south.

John Murray subsequently campaigned for a British Antarctic expedition to explore the region more fully. However, disagreement between scientists and geographers over the relative importance of exploration and scientific research meant that it was W.S. Bruce and the Scottish National Antarctic Expedition, and expeditions from other nations, that were most effective in continuing Southern Ocean research in the early twentieth century.

MARGARET DEACON

See also **Antarctic Bottom Water; Bruce, William Spiers; Crozet Islands (Îles Crozet); Heard Island and McDonald Islands; History of Antarctic Science; Kerguelen Islands (Îles Kerguelen); Marine Biology: History and Evolution; Prince Edward Islands; Royal Geographical Society and Antarctic Exploration; Royal Society and Antarctic Exploration and Science; Scottish National Antarctic Expedition (1902–1904); Sediments and Paleoceanography of the Southern Ocean; Southern Ocean: Biogeochemistry**

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CHANTICLEER EXPEDITION (1828–1831)

The voyage of HMS *Chanticleer,* a gun brig of 237 tons, was first proposed by the Board of Longitude in 1826. The instructions were subsequently drawn up by the Royal Society. The purposes of the voyage were to ascertain the true figure of the Earth by a series of pendulum experiments, mainly in the Southern Hemisphere, to determine the longitudes of various ports, and to undertake observations of meteorology, magnetism, ocean currents, and other items of importance to nautical science.

Captain Henry Foster, FRS, was appointed to the command. He had been awarded the Copley Medal of the Royal Society for his work as astronomer during Sir William Edward Parry's third Arctic voyage of 1824–1825 and had earlier carried out pendulum experiments in South America and Greenland. He was one of the ablest scientific officers in the Royal Navy and his death by drowning in the River Chagres, Central America, towards the end of the expedition in February 1831, was a great loss. A particularly fine memorial to Foster can be found in the parish church of Woodplumpton, near Preston, where his grieving father was rector. The command of *Chanticleer* was subsequently taken over by First Lieutenant H. T. (later Sir Horatio) Austin, who had been in HMS *Fury* in 1824–1825 and was later commodore of the Franklin search squadron, 1850–1851, both voyages to the Arctic.

One of the most notable features of the voyage of *Chanticleer* was the series of observations made on Deception Island in the South Shetland Islands, which had been discovered only 10 years previously. Second Lieutenant E. N. Kendall, who had traveled with Sir John Franklin, surveyed the island. His chart was published to accompany his account in the *Journal of the Royal Geographical Society*. The flooded volcanic crater of the island is named Port Foster for the expedition's commanding officer. The only full, published narrative was that by the surgeon, W. H. B. Bentley, who had been directed to preserve specimens in zoology, mineralogy, and geology.

Chanticleer was specially equipped, and a range of expensive scientific instruments was supplied. According to A. G. E. Jones, Webster had earlier corresponded with the Admiralty about a method of preserving meat, and the ship carried a large supply of Donkin's preserved meat, a relatively early use of such provisions. However, a short allowance of food resulted in the consumption of more than 7000 penguins at Deception Island.

The extensive results of the observations from *Chanticleer* were drawn up by Francis Baily, president of the Royal Astronomical Society, and published at the expense of the Admiralty in 1834.

ANN SAVOURS

See also **Deception Island; Royal Society and Antarctic Exploration and Science; South Shetland Islands**

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CHARCOT, JEAN-BAPTISTE

When Jean-Baptiste Étienne Auguste Charcot was born in Neuilly-sur-Seine on July 15, 1867, there was little reason to think that he would become one of France's greatest polar explorers and scientists. His father was a renowned neurologist and head of the Salpêtrière neurological hospital, and he was insistent that his son follow in his footsteps as a medical doctor. Despite from a young age being enamoured of ships and the sea, and dreaming of joining the French navy, Charcot nevertheless followed his father's wishes and eventually qualified as a doctor in 1895.

The year Charcot completed his medical training, his mother died, two years after his father had, leaving the young man extremely wealthy. Charcot immediately changed his medical pursuits to bacteriology, and in 1897 he essentially abandoned medicine altogether. In the meantime, he had become a competent mariner, purchasing a series of progressively larger yachts, each named *Pourquoi Pas?* He had also joined the elite social set in France: His wife was a granddaughter of Victor Hugo; through her Charcot was also related to Edouard Lockroy, the Minister of the Navy; his sister's husband was the proprietor of the powerful newspaper *Le Matin;* and a half sister was married to P-M-R. Waldeck-Rousseau, who was prime minister of France from 1899 to 1902.

In the years around the turn of the century, Charcot made a series of ever-longer cruises, sailing to England, then around Ireland, then to the Shetland Islands and the Faeroes, concurrently engaging in scientific work. In 1902, in the ship *Rose-marine,* Charcot sailed to Iceland, the Faeroes, and Jan Mayen, immediately falling in love with the Arctic, where he would return many times. Upon his return, he commissioned his own 250-ton vessel, constructed to the highest of standards for scientific research, able to winter in the polar regions, and taking advantage of the knowledge gained by his new associate Adrien de Gerlache, who had led the Antarctic expedition in *Belgica,* the first to winter in the Antarctic. The costs of the new ship—named *Français*—were so high, however, that even Charcot's fortune proved insufficient, so that he eventually installed an underpowered 125-hp engine, which would later prove problematic in the Antarctic.

Charcot planned for his first cruise in *Français* to be to the high Arctic, but news of the efforts to relieve the Swedish expedition under Otto Nordensjöld helped change his mind and turn him toward the area of the Antarctic Peninsula, where his first expedition (1903–1905) explored and conducted scientific observations. At the end of the expedition, Charcot sold *Français,* which had been damaged, to the Argentine government and returned to France to find himself, with the help of publicity from *Le Matin,* a national hero. His wife divorced him on the grounds of him having deserted her to go to the Antarctic, but he soon remarried. In addition to press support, he now had government sponsorship, which allowed him to build a new, larger, more powerful ship—which he again named *Pourquoi Pas?*—and to lead another expedition to the Antarctic Peninsula region (1908–1910).

In 1911, Douglas Mawson unsuccessfully tried to purchase *Pourquoi Pas?* for his Australasian Antarctic expedition, but instead the ship was designated as a French marine research laboratory, of which Charcot was appointed director. In the next two years Charcot made two voyages to Jan Mayen, and then during the First World War he commanded "Q-ships," which were designed to destroy German submarines.

After the war, Charcot began a series of yearly cruises in *Pourquoi Pas?,* spending about three months each year in the Arctic, North Atlantic, or Bay of Biscay. He first visited Greenland in 1925, and thereafter spent much time exploring the East Greenland coast, and helped establish the French research station at Scoresby Sund for the International Polar Year (1932–1933). In 1928, he searched the edge of the ice pack for Roald Amundsen, who had himself disappeared while searching for the members of Umberto Nobile's expedition on the dirigible *Italia*.

On September 16, 1936, leaving Iceland for France (after having been to East Greenland), *Pourquoi Pas?* was caught in a violent storm and foundered on the rocks off Aftanes. Charcot and all but one member of the crew were lost. He was later honoured with a national memorial ceremony attended by the President of France.

BEAU RIFFENBURGH

See also **Amundsen, Roald; Antarctic Peninsula; Australasian Antarctic Expedition (1911–1914); de Gerlache de Gomery, Baron Adrien; French Antarctic *(Française)* Expedition (1903–1905); French Antarctic *(Pourquoi Pas?)* Expedition (1908–1910); International Polar Years; Mawson, Douglas; Nordenskjöld, Otto; Swedish South Polar Expedition (1901–1904); Swedish South Polar Expedition, Relief Expeditions**

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CHEMICAL OCEANOGRAPHY OF THE SOUTHERN OCEAN

The chemistry of the waters of the Southern Ocean is determined by two dominant factors. The first is the physical chemistry of the system (that is, the chemistry determined by Gas Laws, solubility of ions, etc., as well as the interaction with physical oceanographic features such as density-driven currents, air-sea exchange, etc.), and the second is the influence of biological processes. Chemical forms discussed herein include dissolved gases (oxygen and carbon dioxide), macronutrients (nitrate, phosphate, silicic acid), micronutrients (iron), and dissolved organic matter.

The concentration of gases in Antarctic waters is largely a function of their solubility, which in turn is determined at equilibrium by their partial pressure (the percentage in air by volume) and temperature. Oxygen and carbon dioxide are more soluble at low temperatures, so that surface waters of the Southern Ocean have higher concentrations than in temperate or tropical regions. Both are also influenced by phytoplankton (single-celled photosynthetic organisms), which add O_2 during growth (and remove CO_2), and in subeuphotic (dimly lit) waters, oxygen is used by microbial respiration (which generates carbon dioxide). Phytoplankton also remove nutrients along with CO_2, and they are regenerated in deeper waters as well. Thus biological processes couple gases and nutrients in both space and time. Therefore, a typical vertical profile of oxygen would have high concentrations at the surface (often at or above saturation), reduced levels from c. 200–1000 m, and slightly increased concentrations to the bottom. Carbon dioxide concentrations would be the inverse of the oxygen levels. Suboxic and anoxic conditions are extremely rare in Antarctic waters.

Exchanges of gases also occur between the ocean and atmosphere, and their magnitudes are determined by the gradients between the two. Because atmospheric carbon dioxide concentrations are increasing due to anthropogenic effects, the Southern Ocean (south of 50° S) as a whole has become a sink for CO_2; that is, there is a flux of CO_2 from the atmosphere to the ocean. This has been determined through the use of global climate models because observations cannot be taken simultaneously throughout the entire Southern Ocean. The models converge on the magnitude of the sink, and also show that the size of this sink has increased in the past 25 years. Predictions suggest this trend, along with the increasing concentrations of atmospheric CO_2, will continue in the next century (Caldeira and Duffy 2000).

Ice can greatly restrict the exchange of gases with the atmosphere. For example, in the Ross Sea carbon dioxide accumulates under the sea ice during winter (when no photosynthesis occurs and respiration continues at low rates), and late winter CO_2 concentrations (that is, total inorganic carbon concentrations) exceed those of seawater in equilibrium with the atmosphere by at least 100 μatm. Equilibrium conditions (c. 373 μatm) are approached in non-ice-covered regions.

Substantial regional differences in dissolved oxygen levels occur. For example, oxygen concentrations at 100 m near 65° S can exceed 8 mL L^{-1} in the Southeast Pacific, but are <5 mL L^{-1} north of George V Land (Gordon and Molinelli 1982; Orsi and Whitworth 2005). In waters 2500 m deep, oxygen concentrations are all greater than 4 mL L^{-1}. Waters farther south generally contain more oxygen than those in the north (50° S) by about 1 mL L^{-1} due to the colder temperatures and greater solubility near the continent.

Macronutrients, such as nitrate (NO_3), phosphate (PO_4), and silicic acid ($Si(OH)_4$), are required for the growth of phytoplankton, and therefore are part of the biogeochemical cycling of organic matter in the ocean (as are oxygen and carbon dioxide). Nutrients are incorporated and chemically reduced by phytoplankton into body tissues in the euphotic zone, where they ultimately are eaten or sink. The generation, transformation, and unidirectional transport of organic matter from the surface by oceanic biota to depth is called the biological pump. In deeper waters other organisms use this material as food, and in that process elements are recycled back into the original (oxidized) form. Therefore nitrate and other macronutrients have similar profiles; that is, reduced concentrations at the surface, increasing levels below the euphotic zone, and nearly constant concentrations below some 500–1000 m.

Surface waters in the Southern Ocean exhibit extreme seasonality due to the seasonal changes in solar input (which in turn controls ice formation). Gas concentrations and nutrients also show marked seasonal differences (Gordon and Molinelli 1982). For much of the year when biological processes occur at low rates, nutrient concentrations are at their seasonal maxima; conversely, during the short but intense growing season in austral summer, nutrient concentrations reach their minima. Surface nitrate concentrations are high, largely because of the continuous upwelling of deep water at the Antarctic Divergence. Concentrations range from 20–30 μM (1 μM = 10^{-6} moles per liter of seawater, with a mole of any substance being its mass numerically equal to its molecular weight in grams), and only in restricted areas are the levels reduced to <5 μM. A small north-south gradient in NO_3 concentration also occurs between the Antarctic Divergence and Convergence, where concentrations drop to c. 12 μM.

Phosphate concentrations mirror those of nitrate, with maximum concentrations in deep waters being >2.25 μM. Surface concentrations can drop below 1.0 μM. The ratio of nitrate:phosphate in the Southern Ocean is 15.9, similar to that of the entire ocean. Geographic variations are less pronounced than those of nitrate. Silicic acid concentrations (also known as silicate) are among the highest in the world's oceans, and at 3000 m can exceed 150 μM south of Africa. Surface values range from near zero to >90 μM. The extremely low values occur in areas near the Polar Front after the seasonal phytoplankton bloom and reflect a very strong north-south gradient between the Polar Front and the Antarctic Divergence in $Si(OH)_4$ concentrations. South of the divergence values tend to be more constant, except in regions where extensive silicic acid removal by diatoms (a type of phytoplankton) occurs.

All nutrients, after incorporation into phytoplankton cells, must be regenerated and remineralized in the water column. In the case of nitrate, it is reduced upon uptake by phytoplankton and is often released in dissolved form as ammonium by heterotrophic organisms. NH_4 in turn must be oxidized to nitrate by bacteria; therefore, because all of these transformations are biologically mediated, rates of nitrate remineralization are controlled by biological processes. In contrast, the uptake of $Si(OH)_4$ is biologically mediated, but its remineralization is largely controlled by chemical processes and is more independent of biological transformations. In cold waters, biogenic silica is transformed to dissolved silicate more slowly than nitrogen is remineralized (relative to warmer waters), producing some uncoupling between the elemental cycles and vertical distributions in the water column.

Dissolved organic matter (DOM) is a generic chemical group that includes a wide variety of organic compounds (amino acids, lipids, nucleic acids, humic and fulvic acids, polysaccharides, etc.). Each class and compound is biologically and/or chemically oxidized at different rates, and so the composition of bulk DOM varies with depth. Indeed, chemical techniques for the separation and identification of classes of organic compounds in seawater are time consuming and often very difficult analytically, so a clear appreciation of the dynamics of individual compounds is lacking. DOM consists of compounds that include dissolved organic carbon (DOC) as well as those with dissolved organic nitrogen (DON). Each component is measured in a very different manner, and most measurements are available for DOC.

DOM exhibits vertical profiles that are the inverse of those of nutrients, because the source of DOM is biological (photosynthesis, generation during feeding, cellular breakage, etc.). That is, DOM is higher in the euphotic zone and decreases to a low and constant level below c. 300 m. Deep-water values of DOC are c. 42 μM, and horizontal variations occur and are a function of the age of the water (older waters, such as those in the deep Pacific, have lower DOM values). Ratios of DOC:DON in the euphotic zone are about 6, and those in deeper waters near 12. Ranges of DOC in surface waters of the Southern Ocean are from 45–120 μM, with higher values in the regions with extensive biological activity.

Extensive research has been conducted to assess the distributions and effects of dissolved iron. This is in large part in recognition that iron is a major determinant of the nature and extent of phytoplankton growth, which in turn limits energy transformations within food webs. Many uncertainties remain (e.g., the use of organically bound iron by phytoplankton, the oxidation by light of reduced iron, recycling of iron in the euphotic zone), but we have broad outlines of the distribution of iron and its importance to phytoplankton. Iron occurs in the ocean in extremely low concentrations—from 0.05 to 3 nM (1 nM = 10^{-9} moles per liter seawater; 1 μM is 1000 times more concentrated than 1 nM). At such low concentrations, extreme care must be taken to sample water using fastidiously trace-metal-clean techniques to prevent contamination prior to measurement. Surface variations in iron concentrations occur, but due to the relatively limited number of reliable measurements in the Southern Ocean, it is at present difficult to quantify the range of values. Higher levels of iron (>3 nM) are found near islands and coasts, and in waters that have had recent contact with sediments. Ice can also be a source of iron, as Fe accumulates at extremely low rates from dust during the austral winter and is released into the ocean upon melting. Phytoplankton growth reduces iron concentrations to undetectable levels in spring and summer.

There has been a suggestion to fertilize the Southern Ocean with iron to stimulate phytoplankton removal of nutrients and CO_2, with the ultimate goal to reduce the rate of carbon dioxide accumulation in the atmosphere. Small (15 × 15 km) iron fertilization experiments have been conducted in the Southern Ocean (and elsewhere), and all have shown a notable increase in phytoplankton and removal of carbon. It is far less certain how much of this cellular material is exported to depth and permanently removed from the surface. Much concern about the environmental impacts of this carbon reduction scheme has been expressed (for example, creating anoxic zones at depth; disruption of extant food webs; stimulation of nuisance species; harming of non-Antarctic waters), and it presently remains unfeasible to fertilize the waters of the Antarctic to significantly impact atmospheric CO_2 concentrations.

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See also **Antarctic Divergence; Antarctic Surface Waters; Polar Front; Southern Ocean: Biogeochemistry**

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CHILE: ANTARCTIC INSTITUTE

The Antarctic Institute of Chile is a state agency within the Ministry of Foreign Affairs. It was founded in Santiago on February 28, 1964, by presidential Decree No 103. Ambassador Raul Juliet proposed this initiative to the Senate Committee on Foreign Affairs (Chilean Parliament) during the hearings for a law (Arts. 4, 5, 6) to reorganize the Ministry of Foreign Affairs. At the time the minister of Foreign Affairs was Carlos Martínez Sotomayor, serving in the government of President Jorge Alessandri. The political and economic scenario of the early 1960s in Chile did not allow an independent specific law to create a new government agency, which would certainly have an impact on the national budget and number of state employees.

Chile made an Antarctic territorial claim in 1940. On July 23, 1958, the minister of Foreign Affairs, Alberto Sepulveda, called the attention of the Chilean Antarctic Council to the need to create the Antarctic Institute, as requested by Lucia Ramírez and Germán Carrasco of the Section Antarctic Affairs of the Ministry. Since 1946, Chile had organized thirteen annual Antarctic expeditions, and had built three stations, two on the South Shetland Islands and one on the Antarctic Peninsula. Later, in December 1958, Chile signed the Antarctic Treaty in Washington, D.C., becoming one of the twelve founder nations.

The law describes the functions of the new Institute as the national government agency in charge of the planning, orientation, and coordination of all scientific and technological Chilean Antarctic activities.

Presently the Institute has five sections: Scientific, Logistics, Outreach, Finances, and Administrative all under one director and a deputy director. Last year the Institute headquarters were moved from Santiago to Punta Arenas, following a government decision within the framework of a general plan of decentralization of the state agencies. The Scientific Council and the Financial Committee of the Council for Antarctic Policy assist the director of the Institute on the preparation of scientific programs and budgetary matters.

The Scientific Section is in charge of organizing the national scientific contest. This is open to all qualified scientists, mainly from Chilean universities; specialists from Chile and other Antarctic nations referee proposals. A Scientific Board ranks the projects, based on scientific merit and feasibility, and makes a proposal to the director. Then the annual expedition is planned and a timetable is produced in collaboration with the Logistics and Finances sections.

The head of this section also supervises all scientific publications acting as managing editor of "Serie Científica del Instituto Antártico Chileno," sending all papers to peer reviewers.

The Logistics Section organizes the annual scientific expedition providing assistance, supplies, equipment and transport to all scientists. The Navy and the Air Force at the request of the Institute do transport. It builds and maintains six summer stations, four on the South Shetland Islands and two on the Antarctic Peninsula. The largest one is Prof. Escudero on Fildes Peninsula, King George Island, with laboratory space for ten scientists and the support staff.

The Outreach Section prepares, edits, and publishes a Bulletin and a Scientific Series and several occasional publications on Antarctic science and Antarctic Treaty matters. This section also organizes the annual instruction courses for all participants on Chilean Antarctic activities and supervises the Institute Library. Contents of these courses include science, research, law, and policy such as the Antarctic Treaty, Protocol on Environmental Protection to the Antarctic Treaty, and the Convention on the Conservation of Antarctic Marine Living Resources. This section organizes and promotes the delivery and dissemination of the scientific results through conferences, exhibitions, and events for students and general public. The Institute Library houses a unique collection of books on early Antarctic exploration and history of the development of Antarctic policy, as well as scientific periodicals to support research. It also holds a large collection of maps and navigation charts published by Antarctic Treaty nations.

The Finances Section prepares the annual budget and handles all expenditures related to research, publications, and expeditions. The Administration section deals with personnel, buildings, vehicles, and routine maintenance and inventories.

In the development of scientific research the Institute frequently collaborates with its homologue institutions and universities. For example, since 1990 it has had a program on permanent satellital observations of the continent with the German Spatial Agency (Deutsches Zentrum für Luft und Raumfart).

Since its inception, the Institute has organized and sponsored forty-one Antarctic expeditions, financed more than 420 scientific projects, and published fifty annual issues of the Scientific Series, twenty-five annual issues of the Bulletin, and more than twenty occasional publications and reports. It has sponsored many workshops and scientific meetings including four annual Antarctic Research Congresses.

The Institute is also the headquarters of the National Committee on Antarctic Research, a subsidiary body of the Scientific Committee on Antarctic Research (SCAR), under the aegis of the International Council of Scientific Unions (ICSU). Its members are distinguished Chilean Antarctic scientists. The main functions of this Chilean Committee are to assist the government and the Institute on Antarctic science matters including the preparation of scientific Antarctic programs. The Chilean Committee also acts as a liaison with the international scientific community and its members attend the biannual meetings of SCAR.

The Institute provides technical and scientific assistance to the Department of the Environment of the Ministry of Foreign Affairs. The Institute's director chairs the National Board of Antarctic Affairs, which deals with policy making and planning the Chilean Antarctic activities and participation in Antarctic International fora.

José Valencia

See also **Antarctic Peninsula; Antarctic Treaty System; Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); King George Island; Protocol on Environmental Protection to the Antarctic Treaty; South Shetland Islands**

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CHILEAN SKUA

The total population of Chilean skuas *Catharacta chilensis* is unknown, but appears to be several thousand birds. There is no information available on population trends or changes in the extent of the breeding range but there appears to have been a decrease in recent years. Breeding populations of Chilean skuas are present on the coasts of southern South America, from Chile (Concepción) and southern Argentina to Tierra del Fuego. At sea, birds have been observed as far north as Peru (14° S) and on the Atlantic coast to 22° S and eastward to the Falkland Islands. In recent years, increasing numbers of Chilean skua-like birds have been observed on the South Shetland Islands and the tip of the Antarctic Peninsula.

Chilean skuas are coastal and marine birds and occur predominantly in South American channels and straits. The breeding grounds are mainly on islands and remote mainland coastal areas. The Chilean skuas disperse northwards after breeding. The wintering grounds are mainly along the coasts of Chile and Argentina, extending north to south Peru and possibly east to West Falkland Islands. Migration to Peru has been observed in April.

There are no data on the longevity for this species. Chilean skuas breed annually, returning to the breeding areas in October/November. Chilean skuas breed in colonies, sometimes in high densities. Egg laying (normally two eggs, sometimes one) begins in November. The nest scrape is lined with dead grass. Unlike other skuas, adults show very little aggression against people entering the breeding territories. The chicks hatch after 28 to 32 days.

Very little is known about the food of Chilean skuas. They are predators of chicks and eggs of seabirds, but also feed on invertebrates during low tide and from rubbish dumps near towns. They are known to steal food from other birds (kleptoparasitism), to feed on the shore among kelp gulls *Larus dominicanus,* and to follow fishing boats.

At Puerto Deseado, Argentina, a mixed-species colony of Chilean and Falkland skuas *(Catharacta antarctica antarctica)* has been found in which there are also hybrids of these two species. Some skua specimens with the coloration pattern of a Chilean skua have been observed at King George Island and at the tip of the Antarctic Peninsula. On King George I, a hybrid between a South Polar and a Chilean skua has been breeding successfully with a South Polar skua *Catharacta maccormicki* for at least 12 years. In this bird, the forehead, crown, eye region until the gular stripe, and wing coverts are dark brown. Its chin and throat are orange, and the nape and back of the neck are largely pale. The mantle, foreneck and flanks appear brown-and-white spotted, contrary to the orange-and-brown spotted breast, belly and ventral region. A remarkable feature is the narrow closed orange band of its underwing coverts. The bill and legs are black. A chick of this pair was found dead in the North Atlantic Ocean.

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See also **Antarctic Peninsula; Kelp Gull; King George Island; Skuas: Overview; South Shetland Islands; South Polar Skua; Sub-Antarctic Skua**

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CHINA: ANTARCTIC PROGRAM

The purpose of the Chinese National Antarctic Research Expeditions (CHINARE) is to get a better understanding of the Antarctic and its role in the global climate system and the Earth system, and to make contributions to the peaceful use of Antarctica for humankind.

The Chinese Arctic and Antarctic Administration (CAA), part of the State Oceanic Administration (SOA) in Beijing, is the lead government office responsible for the organization, coordination, and management of the national Arctic and Antarctic planning. Its responsibilities include drawing up an integrated national polar research strategy and policy to guide China's polar research activities; developing a five-year plan to implement the national policy and updating the plan annually; coordinating the yearly national polar research expedition, including logistics; promoting interagency coordination of polar research programs, including logistical planning and data sharing; and coordinating and promoting cooperative polar research programs with other countries and international organizations.

The Polar Research Institute of China (PRIC) in Shanghai is the domestic base for CHINARE and is in charge of running and managing the icebreaker M/V *Xuelong,* Chinese Antarctic Great Wall Station, and Zhongshan Station and servicing logistical needs of CHINARE. PRIC is also the polar research center of China. Regarding science, PRIC is responsible for conducting national polar research expeditions. Its current research fields include glaciology, biology, ecology, upper-atmospheric physics, and marine sciences. It carries out international cooperation and academic exchange activities. It has founded several important laboratories for ultralow temperature experiments, clean analysis, polar biological experiments, ionosphere analysis, aurora and magnetosphere analysis, and marine environment numerical modeling. Scientific data and a great number of samples and specimens of polar meteorites, ice cores, and microorganism isolates collected by all Chinese Antarctic and Arctic expeditions are preserved in PRIC.

Financial support for management and field operations is from government funding. The State Ministry on Science and Technology and the National Natural Science Foundation of China as well as some nongovernmental agencies support the scientific research funding, to which scientists from all scientific fields of any research organizations and universities in China may submit proposals. Those successful can take part in the CHINARE field investigations as an additional part of the national research program.

Chinese Antarctic research—started by collaboration with foreign countries such as Australia, Japan, Argentina, Chile, New Zealand, the United Kingdom, and the United States from 1979 to 1984—has developed greatly. As of 2005, four national five-year programs have been successfully carried out. The First Chinese National Antarctic Research Expedition (CHINARE-1) was dispatched in late 1984 and completed the establishment of Great Wall Station on King George Island, South Shetland Islands (62°12′59″ S, 58°57′52″ W). It was opened on February 20, 1985, and has been a year-round station since its establishment. The station is equipped with vehicles, office building, kitchen, living quarters, clinic/recreation/sports building, weather building, comprehensive observatory building, storehouse, electrical power house, and science building for field sampling and research on sea-ice satellite remote sensing, biology, geology, and environmental study and for routine observations of geomagnetic survey, upper-atmosphere physics, whistle sound, and earthquakes.

In early 1989, CHINARE-5 established the second year-round base—Zhongshan Station at the Larsemann Hills in the Elizabeth Land, East Antarctica (69°22′24″ S, 76°22′40″ E). It opened on February 26, 1989, and has been run as a year-round research station since. It is equipped with heavy snow vehicles for inland traverses and a variety of buildings for office work, living, science, power, storage, communications, weather observation, and medical services. The major scientific activities at the station are glaciology, upper-atmosphere physics, atmospheric science, climate change, sea-ice satellite remote sensing, geology, environment, earth science, and marine science in the Prydz Bay and its adjacent region of the deep ocean.

Twenty-one CHINARE voyages have been carried out to resupply and change over personnel for the two Antarctic stations. These voyages included eighteen marine science cruises, implementing the national marine research programs in physical and chemical oceanography, marine biology, geochemistry, and sea/air/ice interactions in the Southern Ocean. These were carried out by the research vessels *Xiangyang Hong No. 10* (1984–1985), the ice-strengthened vessel *Jidi* (1987–1993), and the icebreaker M/V *Xuelong* (1994–present). Two cruises to the Pacific sector of the Arctic Ocean were successfully completed by the ice-breaker M/V *Xuelong* in 1999 and 2002.

Four inland traverses to Dome A, the highest position on the Antarctic ice sheet, and two geological surveys to the Grove Mountains from Zhongshan Station have been carried out in the past seven years. In 2004–2005, the fourth traverse team arrived at the top of Dome A and a series of investigations and samplings were carried out over 13 days, gaining information in preparation for the establishment of a Dome A station by 2010. The traverse lasted 63 days.

Current ship-based research emphasizes: physical oceanography, marine chemistry and carbon cycling, Antarctic krill, polar microbiological studies on features, processes and adaptation, marine CO_2 and aerosol, and sea-ice processes. Station-based research emphasizes space environmental monitoring and dynamic processes in the cusp region, the recent processes of snow and ice, mass balance and historical climate record in the ice sheet of East Antarctica, ice sheet/ice shelf/ocean interactions, sea ice and climate, the process of climate variability in the Antarctic region and its impact on climate change, geology of the Larsemann Hills and Grove Mountains, historical climate record of ecosystem and process in the ice free areas of Antarctica, shifts of penguin populations with respect to environmental change, meteorology and atmospheric science, geodesy and geographic information, meteorites of the Grove Mountains, and Antarctic environmental monitoring and data information integration systems.

China has been publishing a quarterly, *Chinese Journal of Polar Science,* in both Chinese and English since 1988. The National Polar Archive was established in 1990.

Zhaoqian Dong

See also **Antarctic: Definitions and Boundaries; King George Island; Oases; South Shetland Islands**

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CHINSTRAP PENGUIN

Chinstrap penguins *(Pygoscelis antarctica)* belong to the group of Pygoscelid penguins together with Adélie penguins *(P. adeliae)* and gentoo penguins *(P. papua)*. They breed south of the Antarctic Convergence, mainly on the Antarctic Peninsula south to Anvers Island (64° S) and on the islands of the Atlantic sector of the Southern Ocean (South Shetland Islands, South Orkney Islands, South Sandwich Islands, Bouvetøya, South Georgia). Small colonies in anomalous locations have been found on the Balleny Islands, north of the Ross Sea in the Pacific Ocean sector, while attempts at breeding have been recorded on Cape Horn in South America. Its populations are stable or increasing at present, with estimates running in the millions of pairs. They are by far the most abundant penguins in the Scotia Arc, consuming around 90% of all the krill harvested by all land-based predators in the South Shetland Islands. They breed in colonies ranging from a few pairs to hundreds of thousands. They weigh around 4 kg and show the typical black and white plumage of penguins with a diagnostic thin black line running under the chin. Males are slightly larger than females and have a stouter bill. The maximum dive depth recorded is 100 m, but most dives reach less than 50 m in depth, with a mean dive duration of 90 s. Diving effort is concentrated around midnight and noon. The diet consists mainly of krill, although in certain areas also includes myctophid fish.

Chinstrap penguins breed during the short Antarctic summer on steep slopes and rocky outcrops, which are the first areas freed of snow in the spring. Two eggs are normally laid after a short phase of territory occupation, courtship, and mating. Monogamous pair-bonds may last several years, with 80% of individuals pairing with the same partner in successive seasons. Site fidelity is higher for males, with 90% returning to the same nest site in successive seasons (80% for females). No extra-pair paternity has been detected through DNA-fingerprinting in chinstrap penguins. Nests are mounds of pebbles, which reduce the risk of flooding of nest contents by melt water.

During the 1-month incubation period, both parents take shifts at covering the eggs and maintain the nest by collecting new stones. Predation of eggs by skuas is higher in small colonies, while competition for scarce pebbles leading to fights is higher in large colonies. Siblings hatch with on average one day difference, although hatching asynchrony may be as high as 4 days. Chicks hatched late in the season have poorer survival prospects and grow slower than early-hatched chicks. This seasonal trend is related to a reduced disposition to invest by parents as the season progresses. Late-breeding individuals seem to have a poorer health status than early breeders. Chicks are guarded by one of the parents for several weeks, parents taking shifts at the nest and foraging at sea. The amount of food demanded by chicks increases until both parents must forage daily to satisfy this need. At this point, chicks are left alone in loose aggregations, traditionally called crèches but more appropriately referred to as brood amalgamations. These aggregations help to protect chicks from skua predation by collective defence and spreading of risks. The age at which chicks are left unguarded depends on brood size (single chicks are left at greater ages) and parental condition, and is very variable (20–40 days). Chicks left unguarded at earlier ages experience higher mortality risks.

During the postguard phase, parents arrive at colonies only to feed the chicks, which they attract to the nest site by calling. Parent-offspring recognition occurs apparently strictly by sound. When chicks arrive at the nest site, they are led into so-called feeding chases by the parent running away. These chases manage to separate the two competing chicks, which are fed singly at leisure by the parent by regurgitation. Parents are aggressive towards unrelated chicks during visits and there is no collective antipredator defence of chick aggregations by adults. When chicks are 50–60 days old, parents stop provisioning them, forcing them to go to sea and to an independent life. Late-hatched chicks are left unprovisioned at earlier ages. The first days of independent life are marked by a high mortality, presumably due to problems in finding food and intense predation, mainly by leopard seals *Hydrurga leptonyx*. Structurally larger chicks, which have a higher body condition, are also the ones with a higher probability of surviving this crucial period. Parents in energy balance provisioning grown chicks require 1.7 kg of krill daily to sustain their energy requirements (6000 kJ), while each chick of 40 days would consume 0.5 kg of krill daily. Diurnal foraging trips may cover up to 8–10 h, while in some areas the overnight foraging trips may last almost 24 h.

After breeding, adults spend several weeks foraging intensely at sea to accumulate fat reserves amounting to several kg. These reserves are needed for the moulting fast period, when they renew their whole plumage during a period of two weeks when they cannot go to sea. Pairs moult together at their recent nest site. First-year birds have shorter and slighter bills than adults, and dark facial feathers. Young penguins visit breeding colonies in order to prospect for future nest sites and mates during their first years of life and are intensely attracted by chicks in aggregations, which they at times try to mount. There are reports of individuals breeding at two years of age. Young nonbreeders moult earlier than breeders and close to the breeding colonies, coinciding with the final stage of breeding. Life expectancy of chinstrap penguins is unknown, although probably similar to that of Adélie penguins. Little is known about behaviour during winter, although their movements can cover long distances. One individual was tracked during 4 months at sea during winter and reached 1600 km from the colony in which it had moulted. It spent more than 60% of its time in open water north of the edge of the pack ice. Sea-ice conditions during winter may affect mortality, as shown by a reduction in the number of breeding pairs in the subsequent spring.

JUAN MORENO

See also **Adélie Penguin; Balleny Islands; Birds: Diving Physiology; Bouvetøya; Gentoo Penguin; Leopard Seal; Penguins: Overview; Skuas: Overview; South Georgia; South Orkney Islands; South Sandwich Islands; South Shetland Islands**

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CHRISTENSEN ANTARCTIC EXPEDITIONS (1927–1937)

Lars Christensen was responsible for extending and promoting Norwegian interests in the Antarctic while operating a whaling fleet in the area. Christensen's southern operations followed earlier exploratory ventures, and a period of shore-based whaling under concession in relatively restricted areas. These operations began as access to Arctic waters was being denied, when technology was allowing rapid expansion of pelagic whaling, and when the 1926 Imperial Conference was moving towards control of considerable areas of the continent. As exploratory voyages, Christensen's expeditions might be considered intermediary between private, poorly financed expeditions and those more publicly sponsored (Bogen 1957): certainly Christensen sought no support for his ventures.

Conventionally, Christensen's expeditions have been considered as a series of nine single-ship ventures, but they were often not, being integrated into more general, seasonal whaling activities involving tankers, factory ships, and catchers under his command. Here, details are summarized, with an emphasis being placed on the ships *Odd 1, Norvegia,* and *Thorshavn,* but others were involved. There are several accounts of most voyages, and repetitions have produced some conflicts of dates (and occasionally places); further, positions were not always accurate, and features were variously named. Some discrepancies of date or event are indicated, as are some instances where only one author provided specific information.

Christensen's Objectives

Christensen provided several reasons for his expeditions, considering some (like his four *Thorshavn* voyages) to combine business and science, whereas others were essentially for scientific and geographical purposes. Often avowing almost altruistic views regarding his activities, while operating commercially, Christensen wanted to enhance Norwegian whaling opportunities, and he considered that his nine expeditions were ''conceived as a Norwegian contribution'' (Christensen 1938: 4) to research and exploration. But other issues were involved. Thus, increased (in extent and area) pelagic whaling influenced all expeditions (Christensen 1938: 4), but there was also the desire to establish a Norwegian Antarctic ''inheritance'' and to ''possess supply depôts'' in unclaimed areas (Christensen 1935: 17, 31). In fact, there was a desire to invoke claims (with some emphasis on ''the whole region between Enderby and Coats Land'' (Christensen 1935: 204), to establish structures to support occupation (as on Bouvetøya, and Peter I Øy), to ''safeguard Norwegian interests'' (Christensen 1935: 222) without restrictions imposed by other nations. While meteorological and oceanographic observations were routinely made, biological and water samples obtained, and whales sought, the existence of some islands and rocks was also to be resolved. Attempts to sketch coastal areas and obtain aerial photographs were paramount at times, with a need to adequately survey newly discovered areas using modern techniques (for example, as on *Thorshavn*'s fourth voyage), all against a background of perceptions of territorial claims, intentions, and changes in Antarctic (and national) politics. The less-overt desire to examine whaling operations, to introduce new technologies, and to maintain or enhance profitability also took Christensen south.

Summary of Seasonal Activities

1926–1927

Odd 1 (156 t whale catcher; leader: Eyvind Tofte; captain: Anton A. Anderssen) undertook a short prospecting voyage from South Georgia (left January 4, 1927). They sailed from Deception Island, South Shetland Islands, on January 12 after coaling from the factory ship *Pythia*. Peter I Øy was sighted early January 17, a landing attempted, the island circumnavigated, and the ship then went south to the pack ice, returning to Deception Island on January 22.

1927–1928

Norvegia (c. 290 t wooden sealer, 350 hp engine; leader: Håkon Mosby; captain: Harald Horntvedt) went from Cape Town (November 19) to Bouvetøya (November 30), which the party annexed (December 1, involving captain and eleven crew) and then made several landings on. They obtained numerous seal skins and built a ''small house'' (Bogen 1957, quoting Horntvedt) during the month spent in the area; many whales were seen. The intended program of searching between Enderby Land and Dougherty Island (of questionable status) to the west was affected by the ship striking an underwater rock on December 3, but they continued south after ''sounding and sealing operations'' until stopped by the pack ice (January 7; Holtedahl 1931) at about 60° S. The increased leaking and a limited coal supply forced a return to Grytviken, South Georgia, which they reached on January 22. The ship docked for repairs, while the scientists continued on other ships (Holtedahl 1931).

1928–1929

The expedition was originally intended to erect a wireless station on Bouvetøya and then go east along the ice edge, but the instructions were later changed. *Norvegia* (leader: Ola Olstad; captain: Nils

Larsen) left Grytviken on November 8, and met the factory ship *Thorshammer* a month later to receive equipment and men for the proposed station. They were in the area of Bouvetøya December 16–21 (Christensen 1935), but the weather prevented the establishment of the station, although two houses were erected. They unsuccessfully searched for Thompson Island and "Chimneys" (December 21–29), and then the ship west to meet *Thorshammer* and its transport, *Thorøy,* for an exchange of material and men (on or about December 31). They bunkered alongside *Thorshammer* January 1–4, the sailed to Deception Bay, where they refueled prior to sailing for Peter I Øy (January 27, Christensen 1935). A landing was made at Peter I Øy on February 1 (Holtedahl 1931), and the next day it was annexed for Norway. Subsequently, a depot was established and local investigations were made. On February 8 the ship headed southwest, reaching about 140° W on February 20. *Norvegia* took a more northerly return route, did not find Dougherty Island, arrived back at Deception Island on March 19, and laid up at South Georgia.

1929–1930

Again it was intended that *Norvegia* would construct a building on Bouvetøya, take aerial photographs, seek whales, and investigate the coasts between Coats Land and Enderby Land and from Kemp Land to Kaiser Wilhelm's Land. Aviator Hjalmar Riiser-Larsen (leader), two planes, gear, and assistants sailed from Sandefjord on August 24 on *Thorshammer*. *Norvegia* (Nils Larsen) was around Bouvetøya October 14–21, when a depot was established. They then met *Thorshammer* to the west and received two aircraft (a monoplane and seaplane) on November 4, and equipment and crew on November 8 (Holtedahl 1931; Aagaard 1944 gives different details). The airman Finn Lützow-Holm was brought from Cape Town on *Thorøy*. *Norvegia* was off Bouvetøya November 11–14 (Holtedahl 1931 gives November 12), a hut was placed on Lars Island and oblique photographs were taken. The ship then went east along the edge of the pack ice, and began sailing south about December 1 when north of Enderby Land (Holtedahl 1931). South of 64° S, land was seen from the seaplane on December 7. Ice and weather affected the ship's movement, but land was again seen on December 22, at which point the plane landed near the coast and the men skied towards an ice-free area. A Norwegian flag was raised near the landing site and a claim made; significantly, this was well before Douglas Mawson's claim at Proclamation Island (Holtedahl, who provides many details, does not mention the ceremony). *Norvegia* then went northwest to *Thorshammer,* picked up coal, and returned to the southeast. They met Mawson on *Discovery* on January 14 and discussed their activities, following which *Norvegia* went east and *Discovery* west. New land was seen from 66°20′ S on January 15, and flown over later that day and the next. The ship affected by storms and ice conditions and sheltered with *Thorshammer* for some days before going west. They made soundings in the Gunnerus Bank on February 1, and found open water on February 16. Two days later, they saw land (Kapp Norvegia), which they overflew. Another flight on February 20 from within Selbukta allowed further sketching of Kronprincesse Märtha Kyst. *Norvegia* turned north on February 23 (Christensen 1935), and the aircraft were transferred to *Thorshammer* (Riiser-Larsen 1930; Holtedahl 1931; Bogen 1957: 63 places airmen on *Thorøy*). They refueled on March 2 and arrived at Cape Town on March 23 with 370 nautical miles (685 km) of coast charted between 43° and 45° E, and more than 200 nautical miles (370 km) to the west.

1930–1931

This voyage was to search for disputed islands, establish a house and depot on Peter I Øy, and circumnavigate the continent. Gunnar Isachsen was scheduled to lead it until Riiser-Larsen took over around Gunnerus Bank. *Norvegia* (Nils Larsen) left Cape Town on October 4, passed Bouvetøya October 14, coaled from *Thor 1* on October 17 at about 57°40′ S 0°28′ E (Isachsen 1932), and unsuccessfully searched for Truls Island. Although the ship's bridge was damaged when refueling from *Falk* in early November, it continued east, refueled from *Kosmos* near the Ross Sea in early December, and searched (December 13–17, though Isachsen 1932 gives slightly different dates) for islands that were of questionable existence. Pack ice prevented access to Peter I Øy on January 2, and the ship bunkered at Deception Bay on January 10–11. They sailed east, passing the South Sandwich Islands and discovering Maud Bank (January 30). On February 9, they met *Thorshavn* (with Riiser-Larsen, the Christensens, and the aircraft) near Gunnerus Bank. Isachsen transferred to *Thorshavn,* while Riiser-Larsen and the planes went onboard *Norvegia,* which then went southwest. Two flights (February 16–17) allowed the mapping of some 200 nautical miles (370 km) of Princesse Ragnhild Kyst (25–33° E), where a flag and documents were dropped. Two flights on February 21 and 23 found more coast before the planes returned to *Thorshammer* on February 24 (Holtedahl 1931 indicates February 25) and Riiser-Larsen joined *Truls*

(February 28). *Norvegia* then sought Pagoda Rocks without success. They reached Bouvetøya on March 8, and spent about a week there; a landing was made at Lars Island, and it was discovered that the hut there, as well as that on the main island, were gone. The expedition arrived at Cape Town in late March, having collected more than 2000 samples, made approximately 120 soundings and occupied more than fifty hydrographical stations.

Thorshavn (c. 11,000-ton tanker; used by Christensen and wife on four voyages) had left Cape Town on January 6 (with Riiser-Larsen and aircraft onboard) to examine fleet activities. They met *Ole Wegger* on January 18, and later joined the factory ships *Falk* and *Solglimt* for oil transfers. They sailed south on January 31 to rendezvous with *Thorshammer* on February 1. Christensen went southwest from 66°49′ S, 75°30′ E on February 4. Using both Thorshammer and *Thorshavn,* they found Fram Bank and (with hindsight) the continent was seen. Continuing west, they joined *Norvegia* on February 9, when the planes and crew were transferred. They then turned for Cape Town, arriving there on February 19.

On February 12, Christensen instructed catcher *Torlyn* (captain Klarius Mikkelsen) to go south and explore the Lars Christensen Land coast. The catcher *Seksern* had found new land that day and was in the McKenzie Sea on February 13 when *Torlyn* reached 68°52′ S, 72°30′ E and later subsequently sighted Cape Darnley (Bjerkø Head). The next day, *Torlyn* followed the barrier northwest, and ice-free areas and mountains were noted before the ship rejoined *Thorshammer*.

1932–1933

Few Norwegian ships operated in 1931–1932, although more than 230 had the previous season. Nevertheless, Christensen decided to involve some ships that year, as he wanted to improve technology and profits, and examine the prospects of electric killing. *Thorshavn* (captain Mikkelsen) left Cape Town with the Christensens aboard on January 25, 1933, to meet *Solglimt* at about 65° S, 41° E. Riiser-Larsen, Hallvard Devold, and Olaf Kjellbotten (intending an inshore sea-ice expedition using dog sleds) were also aboard. En route, Christensen asked *Solglimt* and *Thorshammer* to search the ice edge between 44° and 55° E for potential landing sites. *Thorshavn* met *Thorshammer* on February 4, and offloading took place the next day. They made towards *Vestfold* at about 64°10′ S, 41°20′ E on February 6, and then joined *Ole Wegger,* but bad weather prevented unloading. *Thorshavn* turned south and spied Enderby Land early on February 8, although ice prevented a catcher from reaching Proclamation Island. *Thorshavn* departed *Ole Wegger* for *Vestfold* on February 10, and men, dogs, and equipment were transferred to *Thorshammer* on February 13. *Thorshavn* neared Bouvetøya on February 20, visited Gough Island and Tristan da Cuhna while returning north, and arrived at Rio de Janeiro on March 7.

Thorshammer was off Princesse Ragnhild Land on February 19, when Riiser-Larsen and others landed on the ice at 68°45′ S, 33°50′ E on March 5. An SOS was sent out on March 9 following the breakup of the ice. Although most of the dogs and much of the equipment were lost, the party itself was picked up by the catcher *Globe V,* and subsequently transferred to *Ole Wegger,* on which they arrived at Sandefjord on April 24.

1933–1934

Christensen originally intended that the third *Thorshavn* (captain Mikkelsen) voyage would be his, and the ship's, last. His plan was for it to conduct a circumnavigation, take routine observations and automatic soundings, and use a seaplane (pilot Alf Gunnerstad). *Thorshavn* left Cape Town on December 20, reached *Thorshammer* on December 27, *Solglimt* (65° S, 30° E) on January 2, *Tafelberg* on January 15, and *Ole Wegger* on January 21. Going west, they found shallow water on January 9 following which the Framnæs Mountains were observed. On January 10, accompanied by the catcher *Treern,* they spied more land from both the ship and the air, but the Douglas Islands were not found. Moving east, *Thorshavn* reached 87° E on January 17; the catcher *Ørnen III,* with a plane, entered the ice and found open water at 65°22′ S the next day. Gunnerstad and Larsen flew to 66°40′ S, and then went northwest for 18 nautical miles (33 km), finding completely ice-covered "land" (then named Princesse Astrid Land). Continuing east, with *Solglimt* and five catchers, they made efforts to determine the whaling prospects from the Ross Sea to South Shetland Islands.

Thorshavn's steering gear was severely damaged on February 3, but they turned south towards barrier nevertheless. They reached the ice edge on February 10 at 71°44′ S, 134°11′ W (farther south than any previous ship had ever been in area). The plane continued south to 72°8′ S, and the barrier was seen 35 nautical miles (65 km) away and for about 120 nautical miles (220 km). They followed the ice edge, but fog prevented them from sighting Peter I Øy. Heading north, they found Sars Bank on February 24, and reached Montevideo on February 27.

1934–1935

Thorshavn (captain Mikkelsen) met *Solglimt* on February 4, 1935, to transfer oils, but both quickly moved into the ice to avoid bad weather. The unloading finished late on February 18, following which *Thorshavn* moved south and west. Shallow soundings suggested land nearby, and the coast was seen around noon on February 19. *Thorshavn* found 5 nautical miles (9 km) of snow-free coast on February 20, and Mikkelsen, his wife Caroline, and seven crew members went ashore. They raised the Norwegian flag after a speech, installed a depot, and ate a snack at the Tryne Islands, which it was later realized was not the mainland (Bogen 1957: 85). *Thorshavn* moved south, past Vestfold Hills and Larsemann Hills. The most southerly observation was of the Caroline Mikkelsen Mountains, before the ship coasted along the barrier until stopped by the pack ice. Subsequently, the Sjøvold (Munro Kerr) Mountains were observed, prior to the ship turning west near Fram Bank. *Thorshavn* left *Ole Wegger* on March 3, having coasted along some 275 nautical miles (510 km) of "new" land and arrived at Cape Town on March 13.

1936–1937

Christensen reported extensively (and repetitively) on this, his last voyage south, which was to improve mapping of newly discovered areas. *Thorshavn* left Cape Town on December 28, 1936, with the Christensens, pilot Viggo Widerøe, wireless operator Nils Romnæs, Mikkelsen, and Nilsen, and a seaplane with extra tanks, radios, and "modern" cameras capable of taking overlapping oblique photographs. They joined *Ole Wegger* on January 14 at about 62° S, 88° E. The catcher *Firern* took the plane and crew aboard and, while *Thorshavn* exchanged oils with factory ships, went south. Sounding was carried out at Gribb Bank (61°30′ to 62°10′ S, 87°30′ to 89° E) on January 20, just before *Firern* reported progress. The catcher had been forced west by the weather, and had reached Ingrid Christensen Land after three days, following which it reached King Leopold and Queen Astrid Land. Widerøe and Romnæs photographed the West Barrier (Ice Shelf).

Shortly before meeting *Firern* in an ice harbor on January 25, *Thorshavn* discovered Four Ladies Bank in Prydz Bay. Four flights were made on January 27, from West Ice Shelf to Sandefjord Bay and over Larsemann, Ranvik, and Vestfold hills. Ingrid Christensen dropped a flag on her namesake land; two flights on January 28 then covered parts of Lars Christensen Land. Christensen and the "four ladies" landed at Scullin Monolith and left a depot early on January 30. The plane headed for Framnæs Mountains (Kemp Land) on January 31, and covered 800 km. More coast was seen and photographed on February 1, when 1400 km were flown; the coverage from the West Ice Shelf to Enderby Land had been completed. The aircraft, crew, and Mikkelsen returned to *Thorshavn,* and *Firern* joined *Ole Wegger*. Cape Ann (Enderby Land) was passed on February 2 and, from a flight on February 4, new land was seen (Prince Harald Coast) with Ingrid Christensen dropping a flag at about 69°30′ S, 36° E. This area was photographed the next day, when Princess Ragnhild Coast was also overflown. Flying on February 6, from 69°15′ S, 26° E, a long, inland mountain chain was noted. *Thorshavn* started homewards on February 7, having completed approximately 1600 km of coastal photography.

The Expeditions and Their Achievements

Christensen started exploratory ventures in Antarctic waters with *Odd 1,* a short voyage that encouraged similar activities during the next 10 years, often exploratory diversions coordinated with commercial ventures involving other ships. Christensen's ships were responsible for many soundings, discovery of banks, and the attaining of extended series of meteorological and oceanographic measures. By the end of his expeditions in 1937, he could claim (Christensen 1938: 15) the sketching of some 4000 km, of which approximately half had been photographed. Through his fleet, Christensen was able to promote Norwegian interests and prominence in Antarctica, perpetuating (if not actually establishing) national values there. But quite apart from the scientific work extensively reported in various media, a more geographical (and political) statement had been made—lands had been discovered (or rediscovered) between 75° E and 18° W (Christensen 1935: 213–214). Further, Norwegian names had been sprinkled around the coast and farther inland, and definitive map sheets had been (or would be) produced. Some (for example, Aagaard 1934) claimed that Norwegians had done more than other nations "combined" to "exploit and explore" Antarctica, and Christensen stressed national rights there, as well as commercial access to whales. While his expeditions might have been a "contribution" to knowledge, he nevertheless accepted that the "special motive" was whales (Christensen 1935: 214), which were of major importance to Norwegian local and national economies.

To support whaling, it was considered necessary to have claims to the continental mainland. Christensen ensured governmental approval to claim unoccupied "new" lands for Norway, at least for some voyages, and his activities were associated with, if not stimulated by, political change (Skagestad 1975). Undoubtedly his expeditions occasionally influenced, and were influenced by, international politics relating to the Antarctic. Thus there was, for a period, some tension with Britain, which was initially opposed to Norwegian claims. However, in time, and wanting Norwegian agreement to measures for whale conservation, Britain accepted them and Norway agreed not to advance any claims east of 45° E and west of 15° W. Hence, Riiser-Larsen's attempted claim was not followed by any governmental action by Norway, and, indeed, Mikkelsen made no such mention when ashore in the Vestfold Hills, although it was perhaps considered (Norman and others 1998). The expeditions may be considered as a progressive investigation of whaling opportunities that initially were to the west (*Odd 1,* early *Norvegia* voyages), concentrating on Bouvetøya and Peter I Øy, before a more directed exploration to the east. Circumnavigations, while associated with seeking whale prospects, may also reflect a contemporary display of a national "presence" around the continent itself. Christensen's expeditions may, therefore, be seen as playing a large role in the development of an understanding of Antarctic geography and as a factor in the development of continental geopolitics. In this regard, then, it is unnecessary to consider the importance of individual voyages; rather, the synergistic consequences of all expeditions should be accepted. His efforts may also be contrasted with the relative contemporary indifference shown by Britain, and more particularly Australia, in the mid-1930s, when there was a transfer of territorial "ownership" but little interest in sending ships south to strengthen the extensive claims.

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See also **Australasian Antarctic Expedition (1911–1914); Aviation, History of; Christensen, Lars; Deception Island; Mawson, Douglas; Riiser-Larsen, Hjalmar; South Georgia; South Shetland Islands; Whaling, History of**

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CHRISTENSEN, LARS

The major ship owner and whaling magnate Lars Christensen was born in Framnæs (Framnes), near Sandefjord, Norway, on April 6, 1884. His father Christen and mother Augusta Frederikke were part of the local (Vestfold) establishment. Doubtless influenced by his father's maritime businesses, he attended middle school and then business colleges in Germany and Norway and worked in shipping offices in Sandefjord, England, and Germany. In 1907, Christensen visited the United States and Canada to investigate whaling, and he became involved with ship-owning and whaling ventures off the Americas and Africa while, with his brothers, becoming increasingly active in his father's company. He was vice-consul (later consul) for Denmark from 1909 onwards.

Christensen married Ingrid Dahl, daughter of Thor Dahl, another entrepreneurial ship owner and merchant, in 1910. By 1921 he was chairman of what became Thor Dahls Hvalfangerselskap A/S, a business complex that incorporated his own company. Earlier interested in the potential of waters between Enderby Land and the South Shetland Islands, Christensen's association with Antarctic whaling and exploration began in 1927 when he sent *Odd 1* west of South Georgia. He made four voyages south with his wife between 1930 and 1937, visited various ships, landed on Gough Island and Tristan da Cuhna, and circumnavigated the continent. The *Thorshavn* voyage in the 1936–1937 season, with the Christensens aboard, provided oblique photographs of eastern Antarctica taken by Viggo Widerøe and Nils Romnæs, which, with observations made from Christensen's ships, enabled production of an atlas of coastal features between 20° W and 80° E. Christensen's fleet was modern and developed around pelagic operations, with factory ships and associated catchers; soundings, oceanographic information, and meteorological data were extensively obtained on exploratory voyages. He was probably the first to consider aerial spotting of whales, carrying aircraft on some voyages and using helicopters in 1952–1953.

Changes in whaling economics and regulations, and perhaps differences with other whalers, modified Christensen's later activities. Christensen established an American cargo/passenger company in 1938 and later expanded into various shipping, nylon, and oil and gas industries. He moved to the United States in 1940 and was attached to the Norwegian embassy in Washington for some six years. Although not working directly for Nortraship during the Second World War, he was chairman of its whaling committee. Following the war, he spent time in America and Norway, but also led Thor Dahl A/S to renewed prominence in whaling.

Areas of Antarctica were discovered by his crews and claims made to Peter I Øy and Bouvetøya, quite apart from Dronning Maud Land, resulted largely from his activities, variously portrayed as purely for scientific or geographic purposes, or as combining science and business. Christensen advocated Norwegian interests and "rights" in Antarctica, seeking access to the continent and its resources. He promoted such views by, for example, diverting ships to explore, encouraging media interest, funding reports of expedition results, lecturing, and producing accounts in various languages. He established the Kommandør Chr. Christensens Hvalfangstmuseum (whaling museum) in 1917, and later sponsored other museums and sculptures in Sandefjord. Christensen's work attracted numerous national and international awards. He died in New York, on December 10, 1965, at age 81.

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See also **Christensen Antarctic Expeditions (1927–1937); Gough Island; Whaling, History of**

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CIRCUMPOLAR CURRENT, ANTARCTIC

Introduction

The Antarctic Circumpolar Current (ACC) flows from west to east along a roughly 25,000 km long path circling the continent of Antarctica. In terms of transport, the ACC is the largest current in the world ocean, carrying about 135 Sverdrups (Sv, 1 Sv = 10^6 m^3 s^{-1}) through the Drake Passage. The ACC connects the ocean basins, allowing a global ocean circulation pattern to exist that strongly influences water property distributions and regional and global climate.

The Drake Passage between South America and Antarctica is the only band of latitudes in which the ocean circles the Earth, unblocked by continents. This geographical "accident" has profound implications for the global ocean circulation and climate. The ACC flows through this gap and acts to isolate

Antarctica from the warm waters to the north. The present glacial climate of Antarctica was not established until the circumpolar channel was opened by the separation of South America from Antarctica 30 Ma.

The ACC affects global, as well as Antarctic, climate. Because the major ocean basins are nearly surrounded by land except at their southern boundary, the ACC is the main means of exchange of water between the oceans. The transfer of water by the ACC smooths out differences in water properties between the basins. More importantly for climate, the ACC connects the ocean basins to form a global-scale circulation pattern known as the overturning (or thermohaline) circulation. The overturning circulation is the primary way the ocean transports heat around the globe. Without the ACC, the global system of ocean currents and heat transport, and hence climate patterns, would be very different than it is today. Southern Ocean ecology and global biogeochemical cycles are also strongly influenced by the ACC and overturning circulation.

Observations of the ACC

The existence of a moderately strong current setting ships to the east at high southern latitudes was noted by early explorers. For example, James Clark Ross found his position was consistently further east than expected based on his reckoning and concluded there must be an eastward current in the region east of Îles Kerguelen. A rapid transition from warm to cold waters as ships passed from north to south was noted by many mariners, a feature that became known as the Antarctic Convergence and which is now recognised as marking one of the current cores of the ACC.

Most of our present understanding of Southern Ocean currents is based on three major circumpolar expeditions carried out in the last century: the *Discovery II* voyages in the 1930s; the monumental decade-long survey conducted by the *Eltanin* in the 1960s and early 1970s; and the circumpolar "snapshot" obtained by the World Ocean Circulation Experiment (WOCE) in the 1990s. The atlases produced by the *Eltanin* and WOCE expeditions provide useful illustrations of many of the features described in this article (see Further Reading). The comprehensive program of measurements carried out in Drake Passage in the late 1970s and early 1980s as part of the International Southern Ocean Studies (ISOS) experiment was another major milestone in ACC research. In recent decades, satellite remote sensing and computer models of ocean circulation have provided new insights into the nature, dynamics and variability of the ACC.

Structure of the ACC

Water properties at a given depth change dramatically as the Southern Ocean is crossed from north to south. Surfaces of constant temperature, salinity, density and other properties slope upward to the south. As a result, density layers found at 3000 m depth in subtropical latitudes approach the sea surface near Antarctica.

The shoaling of density surfaces to the south is associated with the strong eastward flow of the ACC. Tilted density surfaces create pressure forces which drive ocean currents and an accompanying Coriolis force to balance the pressure force. (This balance of forces, known as geostrophy, describes the dynamics of all large-scale ocean currents.) An increase in density to the south, as found in the Southern Ocean, supports an eastward flow (relative to the sea floor), as observed in the ACC. A map of the elevation of the sea surface (dynamic height) shows how the position and intensity of the current varies along its circumpolar path. Contours of dynamic height are approximate streamlines for the flow, so the current flow is rapid in regions where the contours are closely spaced and weak in regions where the contours are widely separated.

The shoaling of temperature, salinity, and density surfaces to the south occurs in a series of steps, or rapid transitions, rather than as a uniform slope across the Southern Ocean. These rapid transitions are known as fronts. Because the strength of an ocean current is proportional to the magnitude of the density gradient, each of the fronts is associated with a maximum in velocity. Most of the flow of the ACC is concentrated in the fronts, with lower speeds observed between the fronts. The zones between the fronts also tend to coincide with regions of relatively uniform water properties at each depth. The ACC fronts, unlike many fronts at lower latitudes, extend from the sea surface to the sea floor. The current jets associated with the fronts therefore also extend throughout the water column. The mean current speeds of the ACC jets are relatively modest, typically less than 0.5 m s^{-1} (about 1 knot), with much weaker flow between the jets. However, because the current is broad and deep, it carries a very large transport.

Early studies of Southern Ocean currents were based on oceanographic surveys with widely separated stations. These low-resolution transects usually revealed a single broad front or transition between warm water to the north and cold water to the south, which became known as the Antarctic Convergence, and later the Polar Front. High-resolution sampling reveals three main ACC fronts. From north to south, these fronts are the Subantarctic Front, the Polar Front and the southern ACC front. The southern limit of the ACC domain is defined by the "southern boundary of the ACC," the southernmost streamline to pass through Drake Passage, which is also often associated with a weak front and current core.

The three main fronts of the ACC are circumpolar in extent and found on any north-south transect across the Southern Ocean. Because the fronts extend to the sea floor and the stratification in the Southern Ocean is relatively weak, the position of the fronts is strongly influenced by the bathymetry. Major ocean ridges can deflect the fronts north or south by hundreds of km (e.g., in the Pacific sector).

Between the fronts lie zones with more or less uniform physical and chemical properties (at any given depth). The Subantarctic Zone is found between the Subantarctic and Subtropical Fronts, north of the ACC. The Polar Frontal Zone lies between the Subantarctic Front and the Polar Front. The Antarctic Zone is found south of the Polar Front. Within each zone, the water properties tend to be similar at each depth and follow a similar seasonal cycle. For example, the Subantarctic Zone is characterized by very deep surface mixed layers in winter and low nutrient concentrations (close to zero for silicic acid and somewhat higher concentrations of nitrate and phosphate). The Antarctic Zone is characterized by fresh surface waters, shallow summer mixed layers and high concentrations of major nutrients like nitrate and silicic acid, but low concentrations of micronutrients like iron.

The zones delimited by the fronts of the ACC also define biogeographic zones populated by distinct species assemblages. For example, waters south of the Polar Front tend to be dominated by large phytoplankton such as diatoms (who need silicic acid) and large zooplankton, while coccolithophores and small zooplankton dominate north of the Subantarctic Front. The distribution and foraging patterns of larger animals (e.g., fish, sea birds, and marine mammals) are also influenced by the frontal structure of the ACC. In some cases, the fronts themselves tend to be associated with higher primary productivity, although the strength of this association varies with time and location. The currents of the ACC can also play a direct role in ecosystem dynamics, for example by carrying krill and larvae from the Antarctic Peninsula to South Georgia.

The ACC is not the only important current system in the Southern Ocean. A westward flow is found near the shelf break and upper continental slope along much of the continental margin of Antarctica. Within the large embayments of the Weddell and Ross Seas, clockwise-rotating (cyclonic) gyres are found. Smaller gyres exist at a number of other locations between the ACC and the coast. The ACC is not isolated from these other current systems: the northern side of the gyres essentially merges with the ACC in some regions and water masses are exchanged between the ACC system and the currents to the south.

Eddies and Variability of ACC Fronts

While the three fronts of the ACC can be identified at all longitudes around Antarctica, details of the frontal structure vary around the circumpolar path. Major fronts merge in some locations, and in others the fronts split into multiple branches that remain distinct for thousands of kilometres downstream. Satellite remote sensing and high-resolution numerical models have revealed that the ACC often consists of multiple filaments, rather than the three main fronts typically found in long-term average climatologies. However, despite the complexity of the frontal structure of the ACC, the fronts are remarkably robust features of the Southern Ocean that can be identified in any cross-ACC transect with sufficient spatial resolution.

The position of the fronts varies with time, but generally over a relatively small latitude range at any given longitude (typically ± 1 degree of latitude). The variability is larger downstream of major bathymetric features and in regions where the ACC fronts interact with the strong boundary currents of the subtropical gyres to the north (e.g., south of Africa).

The variability of the ACC fronts is driven to a large degree by dynamical instabilities of the frontal jets. The instabilities cause the fronts to meander and spawn rings and eddy motions. The ACC has some of the most vigorous eddy activity observed in the ocean. Eddies are produced when dynamical processes release some of the energy stored in the sloping of density surfaces across the ACC, converting some of the energy in the mean flow into motions that vary with time, or eddies. This process is called baroclinic instability. The eddies play a fundamental role in the dynamical balance and heat budget of the Southern Ocean, as described later.

Transport

The first robust estimates of the total transport of the ACC were made in Drake Passage in the late 1970s and early 1980s. By combining repeated measurements of the density field with direct current velocity measurements, the total transport was estimated to be 134 ± 13 Sv (the error bar corresponds to one standard deviation).

More recent estimates give similar values. However, most estimates of ACC transport have included only the baroclinic contribution, or the transport carried by currents that change with depth. The baroclinic flow can be calculated from measurements of density made from a ship (and an assumption about a reference level velocity, which for the ACC is usually taken to be zero flow at the sea floor). To measure the total transport (baroclinic plus the depth-independent or barotropic part), direct current measurements are required. To measure ocean currents with the spatial resolution and duration needed to estimate the mean transport of the ACC is a huge challenge, especially outside of the relatively narrow confines of Drake Passage, and so far has not been attempted. For this reason, most of the published estimates of ACC transport refer to the baroclinic flow. As it turns out, the Drake Passage measurements, and a more limited set of observations south of Australia, suggest that the baroclinic transport relative to the sea floor is close to the total transport. Nevertheless, the magnitude of the mean barotropic transport of the ACC remains unknown.

During the World Ocean Circulation Experiment in the 1990s, the transport through Drake Passage was estimated to be 135 ± 10 Sv, close to the estimate from the late 1970s. Because the Atlantic basin is nearly closed to the north of the Southern Ocean, the net transport between Africa and Antarctica must be very close to the Drake Passage transport (to within about 1 Sv). The transport between Australia and Antarctica must be somewhat greater, to compensate for the flow from the Pacific to the Indian Oceans through the Indonesian archipelago. Repeat transects during WOCE suggest the baroclinic transport south of Australia was 147 ± 10 Sv, roughly consistent with estimates that about 10–15 Sv flows through the Indonesian passages.

(Note that while essentially all the transport through Drake Passage is associated with the ACC, this is not the case to the south of Africa and Australia. The latter continents are sufficiently far north that currents associated with the subtropical gyre systems north of the ACC may influence the net exchange of water south of the continents. Similarly, the presence of westward currents along much of the Antarctic margin will also contribute to the net interbasin exchange. For this reason, the net transport across sections between Antarctica and either Africa or Australia is not exactly equivalent to the ACC transport, although the ACC makes by far the dominant contribution.)

As previously noted, the fronts carry most of the ACC transport, in particular the Subantarctic and Polar Fronts. The relative contribution of these two fronts to the total transport varies around the circumpolar path. For example, south of Australia the Subantarctic Front carries four times more water to the east than the Polar Front, while in Drake Passage the transport carried by the two fronts is roughly equal in magnitude.

The transport of water masses by the ACC also changes with longitude. For example, the ACC carries an excess of intermediate density water into the Atlantic through Drake Passage, which is compensated by an excess of deep water leaving the basin south of Africa. These changes in water mass transports by the ACC reflect water mass transformations in the Atlantic basin, where relatively light Antarctic Intermediate Water is converted to denser North Atlantic Deep Water.

The ACC also transports vast amounts of heat, freshwater, nutrients, carbon, and other properties between the ocean basins. Differences in the net transport of heat and freshwater between Antarctica and the other southern hemisphere continents provides an estimate of the net air-sea exchange of these properties over each ocean basin.

The transport of the ACC varies over a range of time-scales. Multiyear deployments of bottom pressure recorders in Drake Passage during the late 1970s and 1990s suggest a standard deviation in net transport of about 8–10 Sv. For periods shorter than about 6 months, most of the variability is due to changes in sea level (i.e., changes in the barotropic flow). Models and sea level measurements suggest these barotropic motions are highly correlated with changes in wind stress and tend to follow bathymetric contours (more precisely, the flow is along lines of constant planetary vorticity, where planetary vorticity is given by the Coriolis parameter (equal to twice the rotation rate of the Earth multiplied by the sin of the latitude) divided by the ocean depth). For longer periods, variations in the density field (and hence the baroclinic flow) also become important.

Dynamics and Forcing

The absence of continental barriers in the latitude band of Drake Passage makes the dynamics of the ACC distinctly different in character from those of currents at other latitudes. Simple wind-driven ocean circulation theory (the Sverdrup balance), which generally does a good job of describing the circulation of the upper ocean in basins bounded by continents, cannot be applied in the usual way in a continuous ocean channel. The dynamical balance of the ACC has therefore been a topic of great interest for many years.

The Southern Ocean has long been notorious as the home of the strongest winds, and roughest seas, on the planet. The strong westerly winds have long been believed to drive the ACC. In fact, early attempts to model the ACC transport using observed winds in an idealized channel with a flat bottom obtained extremely large transports for reasonable values of the friction parameters, suggesting the winds were more than sufficient to drive a strong ACC. And despite the absence of continental barriers, the Sverdrup theory of wind-driven currents has been applied in the Southern Ocean by assuming that relatively shallow bathymetric features act as "effective continents."

However, such calculations assume no interaction between the current and the bathymetry, which we know to be a poor assumption for the deep-reaching ACC. In addition, wind is not the only factor driving the ACC. The atmosphere also drives ocean currents by exchanging heat and freshwater with the ocean, causing the density of sea water to change. Exchange of freshwater can result from precipitation, evaporation and the freezing and melting of sea ice. Because the speed of ocean currents is proportional to the horizontal gradient of density, any process that produces horizontal density gradients will drive ocean currents. In the case of the ACC, both the strong westerly winds and the air-sea exchange of buoyancy play a part in driving the current.

The momentum supplied to the Southern Ocean by the wind needs to be compensated in some way. The question of what balances the wind forcing has been a topic of debate for many decades. Recent studies have confirmed the early hypothesis by Walter Munk and E. Palmén that interaction of the ACC with sea floor topography provides a force to balance the wind. This force, known as the bottom form stress, results when the ocean currents are organized such that there is higher pressure on one side of a ridge on the sea floor than is found on the other side. In the case of the ACC, higher pressure is generally found on the west side of topographic ridges or hills, providing a force from the solid earth to the ocean that balances the wind stress at the sea surface. While these pressure differences are too small to observe directly, realistic numerical simulations clearly show this force balance in action.

Eddies produced by dynamical instabilities of the ACC fronts play a crucial role in establishing the momentum and heat balance of the Southern Ocean. The eddies transfer momentum vertically from the sea surface to the deep ocean, helping to set up the system of deep currents that interact with bathymetry to provide the bottom form stress. At the same time, the eddies carry heat polewards across the ACC, to compensate for the heat lost to the cold atmosphere near Antarctica.

The ACC and the Overturning Circulation

The eastward flow of the ACC is dynamically linked to weaker, but important, circulations in the north-south plane. The distribution of water properties on transects across the Southern Ocean clearly reveal water masses spreading across the ACC. For example, the salinity maximum of the Lower Circumpolar Deep Water and oxygen minimum of the Upper Circumpolar Deep Water can be traced as they shoal from depths of 2000–3500 m north of the ACC to approach the sea surface south of the Polar Front. The high-oxygen, low-salinity waters formed in the Southern Ocean (Antarctic Intermediate Water and Antarctic Bottom Water) can be followed as they cross the ACC and enter the basins to the north.

These distributions reflect an ocean circulation pattern known as the overturning circulation. Deep water spreads to the south across the ACC and upwells at the sea surface. Some of the upwelled deep water is driven north beneath the westerly winds, gains heat and freshwater from the atmosphere and therefore becomes less dense, and ultimately sinks to form Antarctic Intermediate Water. Deep water that upwells further south and closer to Antarctica is converted to denser Antarctic Bottom Water and returns to the north. The result of these water mass transformations is a circulation in the north-south plane that consists of two counterrotating cells.

The overturning cells in the Southern Ocean are linked to the global overturning circulation. The Southern Ocean imports deep water from the basins to the north, and exports bottom water and intermediate water. Recent studies suggest the conversion of deep water to intermediate water in the Southern Ocean is in fact a key link in the global overturning circulation. For decades it has been assumed that the sinking of dense water in the polar regions was balanced by widespread upwelling at lower latitudes. However, measurements of mixing rates and large-scale tracer budgets suggest that mixing in the interior of the ocean is an order of magnitude too weak to support the upwelling required. The conversion of deep water to intermediate water in the Southern Ocean provides an alternative means of connecting the upper and lower limbs of the global overturning circulation.

Eddies spawned by the ACC make an important contribution to the overturning circulation. The eddies transfer mass across the Drake Passage gap, where the absence of land barriers means that there can be no net east-west pressure gradient and therefore no net north-south flow. Furthermore, the same forces that drive the overturning circulation (wind and buoyancy exchange) also drive the ACC. The west-to-east flow of the ACC and the overturning circulations cannot be understood in isolation. The two are intimately linked, and eddy fluxes, topographic interactions, and wind and buoyancy forcing are all important ingredients of the dynamical coupling between them.

Role of the ACC in the Earth's Climate System and Biogeochemical Cycles

The Southern Ocean plays a number of key roles in the earth's climate system. The ACC connects the ocean basins and allows climate anomalies to propagate and influence regional climate downstream. More importantly, without the interbasin connection provided by the ACC there could be no global-scale overturning circulation. In the absence of the ACC, the transport and storage of heat by the ocean, and hence global climate patterns, would therefore be very different than they are today.

The Southern Ocean also has a large influence on global biogeochemical cycles. Upwelling of nutrient-rich deep water south of the ACC returns nutrients to the surface layer, ultimately supporting a large fraction of global primary production. Water masses at the surface of the Southern Ocean absorb gases like oxygen and carbon dioxide from the atmosphere and transfer them to the interior of the ocean when the water masses sink. As a result of the overturning circulation, more of the carbon released by human activities is accumulating in the latitude band just north of the ACC than in any other latitude band.

Summary

The ACC is the largest current in the world ocean, carrying about 135 Sv from west to east around Antarctica. The current flow is concentrated in a number of circumpolar fronts, which extend from the sea surface to the sea floor. The fronts also mark the boundaries between zones with distinct physical, chemical and ecological characteristics. Eddies produced by dynamical instabilities of the fronts play an important part in the dynamics of the ACC. The strong eastward flow of the ACC is intimately connected to an overturning circulation made up of two counter-rotating cells. The transport and storage of heat, freshwater and carbon dioxide by the ACC and the Southern Ocean overturning circulation has a significant influence on global and regional climate.

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See also **Amundsen Sea, Oceanography of; Antarctic Divergence; Antarctic Peninsula; Coastal Ocean Currents; Drake Passage, Opening of; Earth System, Antarctica as Part of; Eddies in the Southern Ocean; Global Ocean Monitoring Programs in the Southern Ocean; Polar Front; Ross Sea, Oceanography of; Scotia Sea, Bransfield Strait, and Drake Passage, Oceanography of; South Georgia; Southern Ocean: Bathymetry; Southern Ocean: Biogeochemistry; Southern Ocean Circulation: Modeling; Southern Ocean: Climate Change and Variability; Southern Ocean: Fronts and Frontal Zones; Southern Ocean: Vertical Structure; Teleconnections; Thermohaline and Wind-Driven Circulations of the Southern Ocean; Weddell, Ross, and Other Polar Gyres; Weddell Sea, Oceanography of; Zooplankton and Krill**

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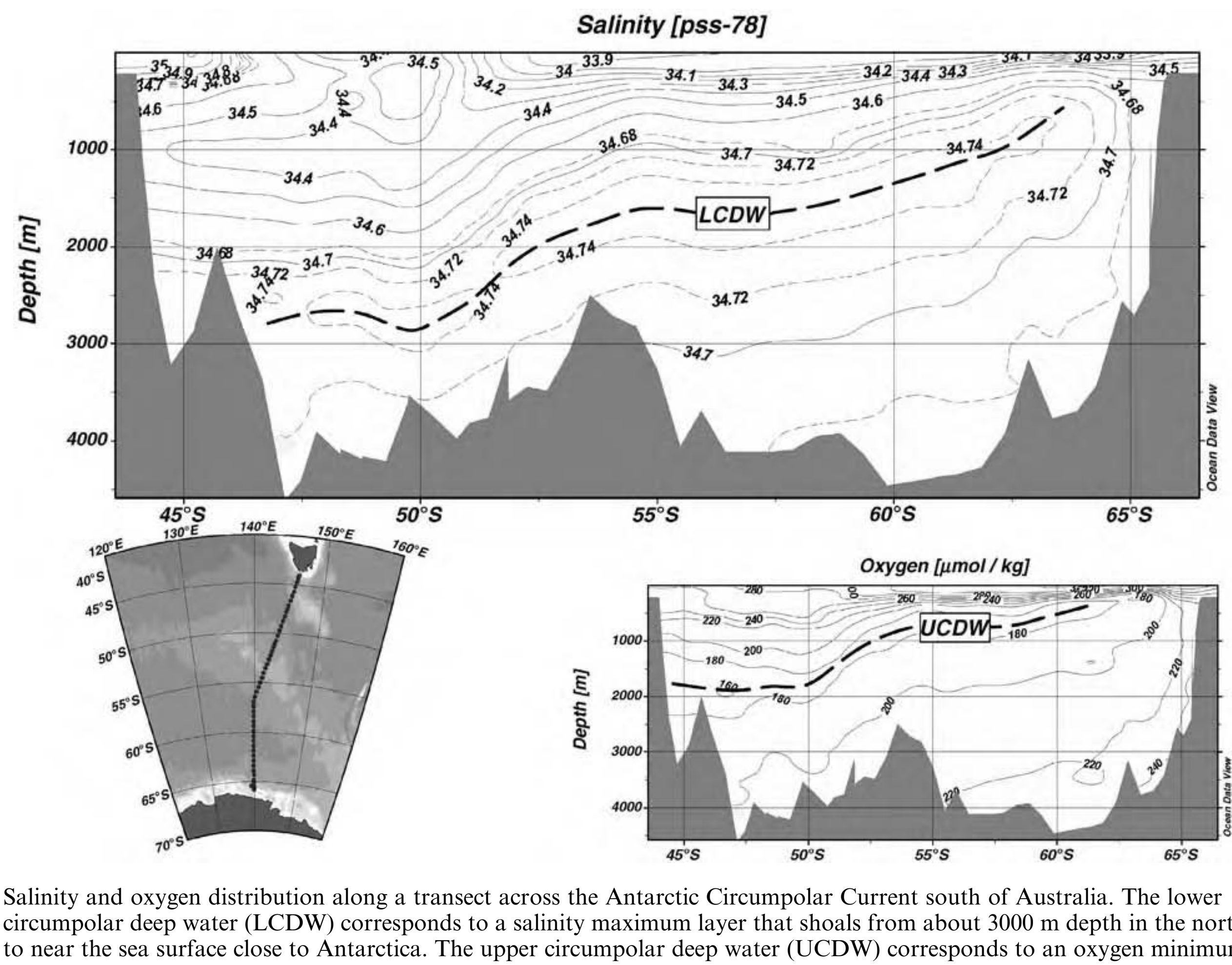
CIRCUMPOLAR DEEP WATER

Circumpolar Deep Water (CDW) occupies most of the volume of the Southern Ocean. The relatively saline CDW lies between fresher Antarctic Intermediate Water above and fresher Antarctic Bottom Water below. North of the Antarctic Circumpolar Current, the CDW is found between depths of roughly 1500 to 4000 m; south of the current, the CDW shoals to within 200 m of the sea surface beneath the fresh Antarctic Surface Water. It is common to distinguish two main types of CDW: the Lower CDW, corresponding to a salinity maximum, and the Upper CDW, corresponding to an oxygen minimum. CDW participates in an overturning circulation in the Southern Ocean which plays an influential role in the climate system.

The source of CDW is North Atlantic Deep Water exported from the Atlantic basin. North Atlantic Deep Water is formed by sinking of dense water in the Norwegian and Labrador Seas, near the northern limits of the Atlantic. The newly formed deep water is carried south in a system of deep currents along the western boundary of the Atlantic to reach the Southern Ocean. The spreading of the North Atlantic Deep Water can be traced by following a tongue of high salinity water at depths between 1500 and 3000 m. Where the North Atlantic Deep Water enters the Southern Ocean, the water mass also corresponds with a maximum in oxygen and minimum in silicate, reflecting the relatively recent formation and rapid transit of this water mass. (Most water masses are "formed" at the sea surface, where exchange with the atmosphere (e.g., of heat, freshwater and gases) produces a volume of water with certain characteristic properties. Once water sinks from the sea surface to enter the subsurface ocean, these characteristic properties can be traced over long distances, allowing circulation paths to be deduced.)

Once the North Atlantic Deep Water reaches the Southern Ocean, it turns east with the Antarctic Circumpolar Current. The salinity maximum water is known as Lower CDW once it joins the Southern



Salinity and oxygen distribution along a transect across the Antarctic Circumpolar Current south of Australia. The lower circumpolar deep water (LCDW) corresponds to a salinity maximum layer that shoals from about 3000 m depth in the north to near the sea surface close to Antarctica. The upper circumpolar deep water (UCDW) corresponds to an oxygen minimum layer that shoals from about 2000 m depth in the north to approach the sea surface on the southern side of the Antarctic Circumpolar Current.

Ocean. The salinity maximum can be followed around the entire circumpolar belt, although the high salinity is gradually eroded by mixing with surrounding fresher waters. Of the roughly $135 \times 10^6\ m^3\ s^{-1}$ of water carried through Drake Passage, approximately two thirds ($90 \times 10^6\ m^3\ s^{-1}$) is in the CDW density range.

No deep water is formed in the northern Indian and Pacific Oceans. The deep layers of these basins are supplied by water masses entering from the south, including CDW and Antarctic Bottom Water. The dense waters of southern origin enter the northern basins in a series of deep boundary currents found on the western side of the ocean basins. The northward flow near the sea floor gradually mixes with surrounding waters resulting in a decrease in salinity and density. Oxygen levels are decreased by mixing and by consumption of oxygen during the decomposition of organic matter falling from above. This altered form of CDW, which is lower in salinity, density and oxygen than its parent water mass, returns to the Southern Ocean to compensate the inflow of denser water near the sea floor. The return flow of deep water from the Indian and Pacific basins forms a distinct oxygen minimum layer in the Southern Ocean which identifies the Upper CDW.

Both the Lower and Upper CDW layers are carried east by the Antarctic Circumpolar Current. At the same time, the salinity maximum and oxygen minimum layers can be traced to the south across the Circumpolar Current. As the water masses spread to the south, they tend to rise to shallower depths, following surfaces of constant density which slope steeply across the current. The poleward movement and shoaling of the CDW is an important part of a large-scale overturning circulation in the Southern Ocean.

As the UCDW nears the sea surface, it mixes into surface waters altered by the overlying atmosphere and by precipitation, evaporation and by the melting of sea ice and glacial ice. These processes reduce the density of the surface layers, which are driven north and east beneath the westerly winds in the wind-driven Ekman layer. Ultimately the water sinks again from the sea surface and supplies the Antarctic Intermediate Water and Subantarctic Mode Water layers. The net result is that UCDW spreads poleward and upwells at high latitudes, is converted to less dense water by air-sea exchange, and is ultimately exported from the Southern Ocean as lighter mode and intermediate water. This circulation pathway is known as the upper limb of the Southern Ocean overturning circulation.

The lower limb of the Southern Ocean overturning circulation involves the Lower CDW. Part of the water that upwells is carried south beneath the easterly winds. Near the continental slope of Antarctica, the water properties are altered through mixing with colder and fresher waters to form Modified CDW, which is transformed further through complex ocean-atmosphere-ice interactions to produce dense Antarctic Bottom Water. The poleward flow of Lower CDW and compensating equatorward flow of Antarctic Bottom Water together form the lower limb of the Southern Ocean overturning circulation.

The two cells of the Southern Ocean overturning circulation strongly influence the physical, chemical, and biological distributions of the ocean. The conversion of CDW into lighter intermediate waters in the Southern Ocean is believed to be the primary way that the upper and lower branches of the global thermohaline circulation are connected. Water masses formed in the Southern Ocean as part of the overturning circulation provide oxygen to (or "ventilate") the intermediate and deep levels of the southern hemisphere oceans. The ocean uptake and storage of atmospheric carbon dioxide is regulated by the Southern Ocean overturning and the upwelling of CDW is the main source of nutrients to Southern Ocean ecosystems.

At high latitudes, the CDW often corresponds with a temperature maximum in vertical profiles, lying between the cold Antarctic Surface Water and the cold Antarctic Bottom Water. As a consequence, the CDW is sometimes referred to as Warm Deep Water, particularly in the Weddell Sea. The reservoir of heat in the CDW can have important consequences. For example, in some locations CDW can reach the continental shelf and provide sufficient heat to melt substantial amounts of ice from ice shelves and floating glacier tongues. The Weddell Polynya of the 1970s was maintained by heat supplied by the CDW, once the stratification that usually isolates the CDW from the surface layer was broken down.

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See also **Antarctic Bottom Water; Antarctic Divergence; Antarctic Intermediate Water; Antarctic Surface Water; Circumpolar Current, Antarctic; Polar Front; Southern Ocean: Biogeochemistry; Southern Ocean: Vertical Structure; Thermohaline and Wind-Driven Circulations in the Southern Ocean; Weddell, Ross, and Other Polar Gyres**

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CLIMATE

Introduction

Understanding the varied climates of Antarctica and the adjacent Southern Ocean has assumed great importance recently, for the following reasons:

- Southern higher latitudes are not isolated from extrapolar regions, including the Northern Hemisphere: Antarctica influences, and also responds to, climate variations elsewhere.
- The discovery of the stratospheric ozone hole, which occurs over Antarctica every austral spring, and the identification of the role of human-made chlorine compounds in ozone destruction have implications for ecosystem and human health globally.
- Polar regions likely are first indicators of contemporary climate changes potentially linked to "global warming." The Antarctic Peninsula is one of the fastest warming areas on Earth, and reduced sea ice and collapsing ice shelves have occurred in that region and elsewhere around Antarctica. Recently, the upper ocean in the Ross Sea has seen decreases in salinity.
- Cross-disciplinary studies of ecosystem variability for Antarctica and the Southern Ocean show close associations between biological activity, sea-ice conditions, and the atmospheric circulation.
- Antarctica's crucial role in past climate changes globally, as indicated in ice cores extracted from the continental ice sheet, and elsewhere, including the Northern Hemisphere.
- Antarctica's ice-free areas, notably the Dry Valleys, may be analogues for the planet Mars and are helping guide planned exploration of that planet.
- Antarctica is becoming a destination for "ecotourists" as well as scientists, and the potential environmental pressures of such activities are a growing concern. While the use of numerical models to improve weather forecasting in this region in support of human activities is critical, much understanding can be achieved with a knowledge of climatology.

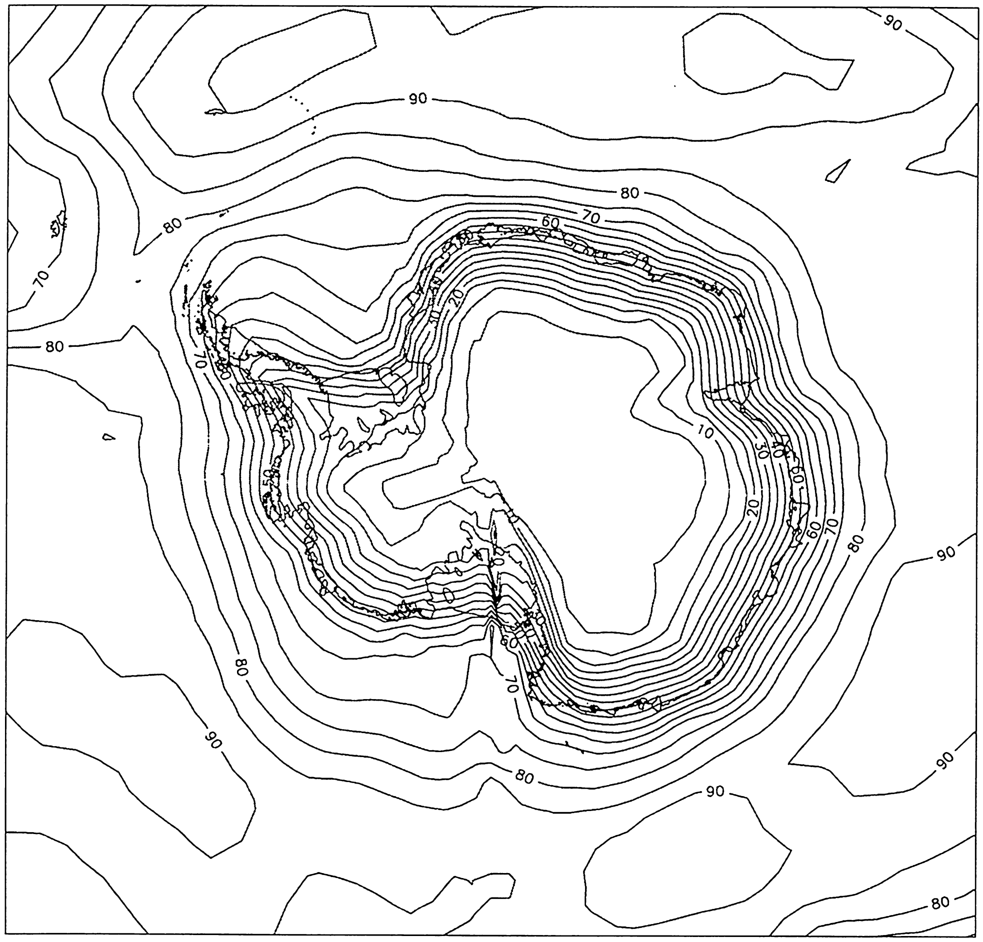
The increased need to understand Antarctic climates has been greatly assisted by advances in monitoring over the past three decades; notably the use of polar-orbiting satellites and surface-based intensive field programs such as the International Trans-Antarctic Scientific Expedition (ITASE). The latter involves drilling many shallow ice cores in transects across Antarctica to identify climate variations and changes within about the past 250 years. In addition, greater understanding has been achieved using numerical models of the atmosphere and ocean to simulate Antarctic climates and their interactions with lower latitudes.

The dominant factor in Antarctic climates is the presence of ice comprising three broad types: continental (land) ice, sea ice, and floating ice shelves. Moreover, the associated negative net radiation "balance" of southern high latitudes helps determine Antarctica's climatic relationships with extrapolar latitudes, particularly the influxes of heat and moisture due to atmospheric cyclone systems. Given the importance of the observation network to the understanding of Antarctic climates, a brief survey of the climatic database is in order.

Climatic Forcing Factors

The ice-covered South Polar region is perennially cold yet with latitudinally strong gradients of temperature and moisture (i.e., humidity, cloud cover, precipitation) located near the Antarctic coast. However, this generalization belies the regional and even local-scale climates that occur, in association with spatial variations in surface energy balance related to different ice types. These Antarctic climates result from combinations of the following physical geographic factors:

1. Elevation. The interior ice sheet of East Antarctica has altitudes of 3000–4000 m, which lowers temperatures and increases dryness (i.e., low humidity, lack of clouds) relative to locations



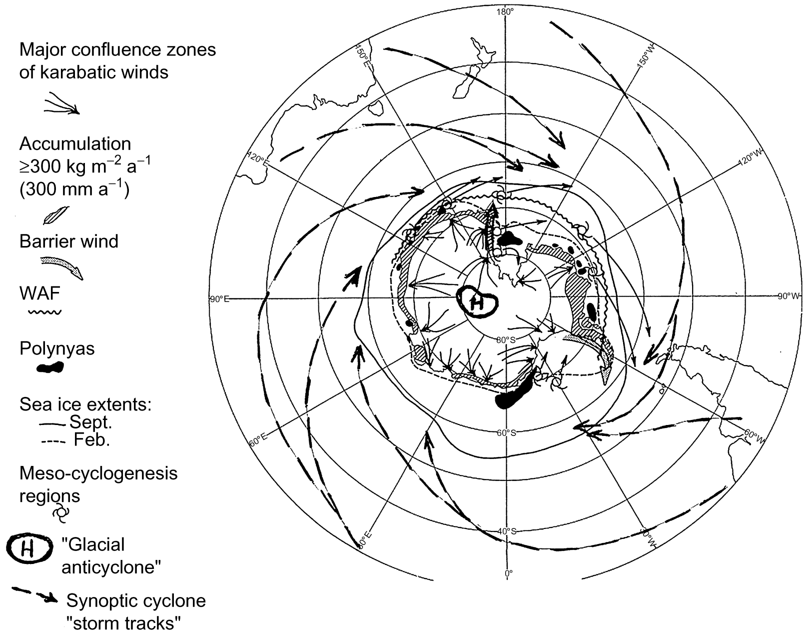
Summer mean cloud amount (%) for Antarctica and adjacent regions of the Southern Ocean, based on data from the International Satellite Cloud Climatology Project. (From Turner and Pendlebury 2004.)

closer to mean sea level (MSL), such as the lower altitudes of West Antarctica and the continent's coastal margins. Thus, the map of mean near-surface air temperature (Ta) closely resembles that of the ice-sheet topography.

2. Latitude location with respect to the prevailing patterns of atmospheric circulation. These are the westerly winds of sub-Antarctic latitudes and "polar easterlies" over the bulk of the continent and which contain, respectively, the mobile frontal cyclones entering the Seasonal Sea Ice Zone (SSIZ) from extrapolar latitudes, and the cold-cored high pressure over the continental interior.
3. The presence and extent of open water (e.g., the ice-free Southern Ocean versus polynyas—nonlinearly shaped—and leads—linearly shaped—contained within sea ice), and the presence and depth of snow on sea ice. Longitudinally, this is evident as relatively mild conditions in the western Antarctic Peninsula versus the frigid ice-covered areas of the Weddell and Ross Seas.
4. Season, particularly the change between open water and ice-cover that occurs every autumn and winter in the SSIZ, and the dominant half-yearly "cycle" of atmospheric pressure, wind speed and precipitation, or Semi-Annual Oscillation (SAO).

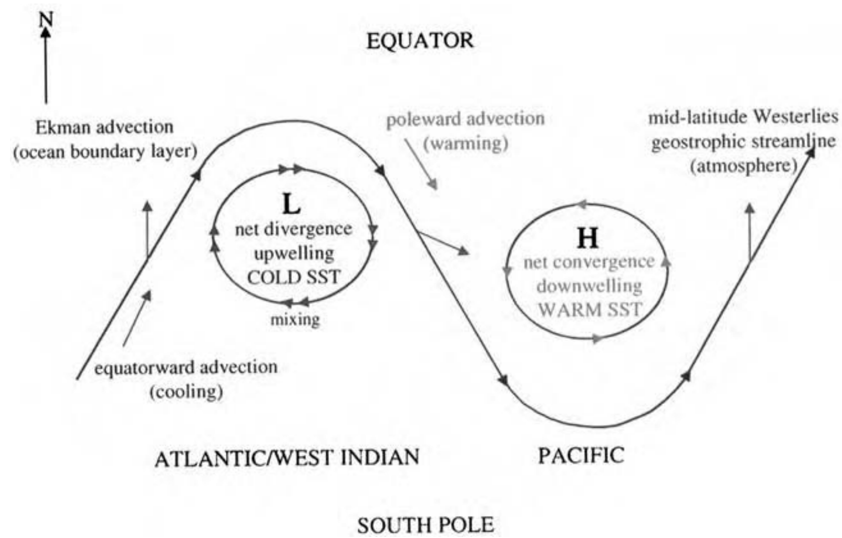
The exact roles of these physical geographic factors in Antarctica's climates, and their mutual interactions, now are discussed. Most of these factors contrast markedly with those responsible for Arctic climates.

- The South Pole is located within a continent, isolating the interior of Antarctica from heat and moisture sources located equatorwards. Thus, Antarctica is the perennial source region of the coldest and driest air on Earth, although this air modifies significantly upon leaving the continent.



Schematic representation of dominant features of the climate of Antarctica and the Southern Ocean, as compiled from various sources. (Adapted from Carleton 1992.) In addition to the sources listed in Carleton, this adaptation includes information from Carrasco et al. 2003 and Simmonds et al. 2003.

- The higher elevations of the ice sheet (“pole of inaccessibility”) are asymmetrical with respect to the South Pole location. Accordingly, the Southern Hemisphere’s cold source is displaced away from the pole towards the Indian Ocean and southwest South Pacific sectors. Similarly, the time-averaged patterns of Ta, sea surface temperature (SST), sea-ice extent near the time of maximum extent, and the troposphere’s geopotential height fields, are displaced towards those areas as a wavenumber one pattern. Modeling indicates that the off-pole location of the highest part of Antarctica explains the large interannual variability of MSL pressure (MSLP) in the Amundsen Sea area.
- Although the ice sheet topographic gradient is relatively slight over much of the interior, it increases sharply closer to the continental margin. This shape promotes radial gravity-induced drainage of cold air, or katabatic winds, that accelerate towards sea level. Conversely, over the interior, winds are relatively light.
- The occurrence of summer when Earth is closest to the Sun in late December and early January provides a short austral summer yet with some of the highest top-of-the-atmosphere (TOA) insolation values on Earth. In combination with the very high reflectivity, or albedo, of the surface, very little insolation is absorbed by the surface to either heat the air or melt snow and ice.
- The sea ice undergoes a large seasonal variation from a minimum in February/March (3×10^6 km^2 area) to a maximum in September/October (20×10^6 km^2). This change virtually doubles the size of the continent, and strongly influences the surface radiation and energy budgets, the upper-ocean temperature and salinity structure, and the receipt of moisture as snowfall at the Antarctic coastline. The regional ice conditions (e.g., the ice latitude extent, ice-water concentration) show a negative relationship to the annually averaged Ta. Similarly, multiyear trends in annual mean temperatures at coastal Antarctic stations are inversely correlated to those of sea-ice extent in broadly similar longitudes, although on a year-by-year basis the relationship is less clear.
- The circumpolar Southern Ocean mediates the interactions of heat, salt, and momentum between high and lower latitudes, including the formation and melting of sea ice. Moreover, the near-surface climates of coastal areas are modified by their proximity to the Southern Ocean relative to the continental interior. Major embayments are sites of floating ice shelves, derived from the continental ice, and are sources of large tabular icebergs that tend to move away from the continent and slowly melt, thereby affecting extrapolar latitudes. The ice shelves help buttress the continental ice sheet; they are particularly sensitive to changes in Ta and the thermal



Schematic showing the interaction between a standing wave couplet (i.e., trough, ridge) and sea surface temperature (SST) anomalies for the Southern Ocean. The waveform is a geostrophic streamline describing the surface high and low in the mean sea level pressure. Deflection of the winds to the left (secondary arrows) is the result of the Coriolis Force, which induces upwelling west (east) of the trough (ridge), but downwelling east (west) of the trough (ridge). (From Milliff et al., 1999.)

characteristics of the water circulating beneath them, influencing upper ocean physical characteristics and sea-ice conditions.

- Although both polar regions are characterized by net radiation deficits at the surface and in the atmosphere, which necessitates the advection of heat into the region from lower latitudes, Antarctica presents a strongly zonal (i.e., latitudinally symmetric) profile to ocean latitudes located to the north that is interrupted only in the Antarctic Peninsula. This geographic zonality has important additional consequences for the climates of southern high latitudes, as follows:

1. The zonal westerly winds attain high speeds at Earth's surface (e.g., "Roaring Forties," "Screaming Sixties"). Aloft, the westerlies undergo only limited annual variation in strength contrasted with their interannual variability, and also the semiannual signal (i.e., SAO). The SAO involves zonal pressure/height and associated wind changes between Antarctica and middle latitudes, peaking over the sub-Antarctic and coastal East Antarctica.
2. In the upper ocean, the zonal circulation reaches a maximum westerly speed in the Antarctic Circumpolar Current (ACC). The ACC position, which shows a close association with the highest seafloor topography, strongly influences the sea-ice spatial configuration near the time of maximum ice extent (springtime).
3. The atmospheric Rossby waves typically have lower amplitudes than their counterparts in the Arctic, and are more barotropic (i.e., the time-averaged ridges and troughs in the pressure/height and temperature fields more or less coincide). This characteristic limits the ability of "standing eddies" to transport much sensible heat into the Antarctic, in contrast with their counterparts in northern high latitudes.
4. As a consequence of the previous factor, frontal cyclones traveling within the westerlies (i.e., "transient eddies") transport most of the sensible heat to Antarctica. Moreover, the flux of moisture to the continent, and snowfall receipts in coastal and near-coastal areas, are strongly influenced by the passage of cyclones.
5. Because of the lack of heat transported by atmospheric standing eddies, the upper ocean participates in the meridional transport of heat via interactions with the frontal cyclones: southerly (northerly) winds occur on the western (eastern) sides of low pressure systems, which induce divergence (convergence) of air in the low-level wind field and upwelling of cold water (downwelling of warm water). When maintained in similar longitudes on monthly and longer time scales, these ocean-atmosphere interactions result in increased salinity west of persistent cyclone high-frequency areas, and decreased salinity east of the cyclone waves. Such an association also is evident in the suite of

anomalies characteristic of the subdecadal scale Antarctic Circumpolar Wave (ACW).
6. The dominant mode of interannual climate variability over Antarctica and the Southern Ocean, or "Antarctic Oscillation" (AAO), is strongly zonal. It involves an antiphase association of the anomalies of pressure/height, temperature, and zonal winds between middle and high latitudes, such that a positive (negative) phase is associated with enhanced (reduced) westerlies over the sub-Antarctic. Other patterns of climate interannual variability, including the Antarctic teleconnections to El Niño Southern Oscillation (ENSO), have associated atmospheric anomalies that are aligned more meridionally.

Climate Broad Types of Antarctica

Given the previous physical geographic and climate forcing factors one can identify, at a minimum, the following four broad regional surface climates in the Antarctic, with subdivisions of these types also possible:

- The SSIZ, extending equatorwards from near the Antarctic coastline to around 55°–60° S at the time of maximum extent. This is a cloudy and stormy zone dominated by the seasonal change from open water to sea-ice cover, and back again. Particularly in East Antarctica, it is possible to identify an innermost (outermost) zone of ice concentration.
- The floating ice shelves, particularly within the Ross Sea and Weddell Sea, comprise a transitional climate type between the southern SSIZ and the continental climates because of the sea water circulating beneath them.
- The western Antarctic Peninsula. Because of the Antarctic Peninsula's extension into sub-Antarctic latitudes, the westerly winds impinging upon the spine of higher topography result in a more marine climate than that to the east (Weddell Sea). However, there are large interannual variations in climate in the western Antarctic Peninsula, especially in winter, which accompany fluctuations in the intensity of the Amundsen Sea mean low pressure system (ASL) and associated sea-ice conditions.
- Continental climates are the coldest and driest, and dominate the ice-covered land surfaces. Regional-scale differences in the severity of continental climates occur due to elevation (cf. East Antarctica and West Antarctica), the exposure to synoptic cyclones that import heat and moisture (cf. the Pacific and Atlantic sides of West Antarctica), and slope/latitude (cf. coastal and interior regions of East Antarctica). Also, the interannual variability of temperature and precipitation tends to be smallest (greatest) in interior East Antarctica (the Pacific side of West Antarctica).

Climatic Consequences of the Net Radiation Deficit

The negative net radiation balance on the Antarctic ice sheet results from the high surface albedo, a loss of longwave radiation, and a highly transmissive atmosphere. For Antarctica's climates, a number of consequences arise from the net radiation deficit, notably the following:

- The Surface-Based Inversion Layer
- The Katabatic Winds
- Oceanic Processes

The katabatic winds are important for upper-ocean processes near the coast, especially in winter. These include the opening of shore leads and "latent heat" polynyas, and new sea-ice production as a result of the very low temperatures. The increased evaporation within coastal polynyas and low-ice concentration areas increases the upper-ocean salinity and, hence, the production of bottom water close to Antarctica. Changes in Antarctic deep water production may feature in long-term climate changes on global scales. For large "sensible heat" polynyas, particularly that which dominated the sea-ice regime of the Weddell Sea during the 1970s, the frequencies of cold-air mesoscale cyclones (i.e., "polar lows") increased around the polynya.

- The Kernlose (Coreless) Winter
- The Semi-Annual Oscillation (SAO)
- Cyclonic Activity and the Poleward Advection of Heat

Because the downward flux of sensible heat (Q_H) from the temperature inversion to the ice sheet is insufficient to balance the energy budget, a net inflow of energy to Antarctica occurs mostly as Q_H advected by the traveling synoptic-scale frontal cyclones. The majority of these cyclones originate in middle latitudes, with each successive stage of development (i.e., open wave → maturity → occlusion or dissipation) occurring closer to Antarctica, in the aggregate. The poleward transport of eddy sensible heat and momentum show a close association with the stages of cyclone development: the poleward heat flux decreases as cyclones evolve from the open-wave to dissipation stages; however, the momentum flux is strongly poleward in the wave stage (i.e., a positively tilted trough) but equatorwards in the dissipation stage (i.e., negatively tilted trough). Thus, the convergence of eddy momentum is strongest, on average, between about latitudes 55° to 65° S. The zone of maximum cyclonic activity is located to the north of the Antarctic Circumpolar Trough (ACT, the circumpolar belt of low pressure), which is demarcated in the MSLP data.

Mean and Variability Patterns of Climate Parameters

Air Temperature

Over the highest elevations of East Antarctica, winter surface temperatures average –60°C to –70°C, or "cold pole." Temperatures are not much warmer in summer (~ –30°C), largely because of the high surface albedo. The ability of milder air masses to penetrate into West Antarctica from the Pacific Ocean ahead of frontal systems, results from the generally low elevations of this part of the ice sheet. In most seasons, the Antarctic Peninsula exhibits an out-of-phase association of temperature anomalies with those on the Antarctic mainland and, in turn, these show relationships to atmospheric circulation. A latitudinal strong gradient of temperature exists along the western Antarctic Peninsula and also for circumpolar stations south of the ACC (60° to 70° S). For the latter zone in winter, the gradient is around 1°C/1° latitude, compared with about 0.6°C/1° latitude for 30° to 60° S, and there are associated strong gradients of SST.

Considerable interannual variability of temperature occurs in the Antarctic Peninsula, of which a substantial portion is related to ENSO. Thus, winter temperatures in the Antarctic Peninsula show associations with the intensity of the Amundsen Sea mean low (ASL) pressure system, which comprises part of the Pacific South America (PSA) atmospheric circulation pattern. When the ASL is strong (weak), typically during a La Niña (El Niño) event, the western Antarctic Peninsula experiences enhanced northerly (southerly) winds and, accordingly, higher (lower) temperatures. As a consequence of the changed temperature advection patterns in the atmosphere, along with the SST anomalies, the sea ice west of the Antarctic Peninsula retreats poleward (advances equatorwards) for a strong (weak) ASL. On the ice sheet, a portion of the interannual variability of surface temperatures is related to ENSO, although this signal varies regionally. Temperature anomalies over most of the continent tend to be negative in the year of an El Niño.

Cloud Cover

A consequence of the decrease in Ta with increasing latitude is a decrease in the atmosphere's ability to hold water vapor, evident as low values of absolute humidity and precipitable water over the ice sheet. Accordingly, cloud cover is at a minimum over the interior higher-elevation areas of East Antarctica, especially in winter: the air subsides and the clouds that do occur consist mostly of cirrus. Conversely, cloud amounts are at a maximum (80%–100%) over the ocean within the SSIZ, resulting from convergence and ascent of air in cyclone systems. Along the Antarctic coastline between these two regions there is maximum variability in cloud cover that results from the passage of synoptic systems and their associated shifts in meridional winds.

Increasingly, attention is being paid to clouds in the stratosphere (i.e., Polar Stratospheric Clouds: PSCs). In addition to their influence on the radiation budget, the frequency and spatial distribution of these clouds is important for rates of ozone destruction because they provide sites for chlorine compounds to become active.

Precipitation

Over much of the ice sheet, the very low humidity values and tendency for air to subside and diverge means that Antarctic precipitation values are low (or "polar desert"). Because direct measurements of snowfall in the Antarctic are unreliable, indirect methods (e.g., moisture budget/mass balance) mostly have been favoured. Recently, the application of mesoscale models to Antarctica yield higher resolution precipitation mean values and temporal trends. On the high plateau, mean annual precipitation is less than about 2 cm yr^{-1} water equivalent. Although the dominant precipitation type is snowfall, clear-sky precipitation ("diamond dust," wind-redistributed snow) contributes substantially to the ice sheet mass balance over interior regions. Along the Antarctic coastline, especially the western Antarctic Peninsula, snowfall amounts are higher by at least two orders of magnitude. Occasionally, mixed precipitation and rain occur in these regions. In the Pacific sector of West Antarctica, relatively few snowstorms dominate the annual snowfall regime, in association with frontal cyclones. Interseasonally, there is an SAO signal in precipitation amounts, especially for coastal Antarctica, that is associated with the latitude variations in the axis of greatest cyclonic activity. Similarly, the high interannual variability of precipitation at coastal stations results from fluctuations in cyclonic activity, at least a part of which is ENSO-related.

Surface Winds

The basic zonal conceptual model of the near-surface wind field over southern higher latitudes (i.e., westerlies, polar easterlies) is complicated by (1) the high elevations of the ice sheet, which induce persistent radial drainage of cold air (katabatic winds) over the continent; and (2) the presence of significant topography, particularly the mountains of the Antarctic Peninsula and the Transantarctic Mountains, which help produce so-called barrier winds over western sides of the major embayments (i.e., Weddell Sea, Ross Sea).

Flow over the continent. The radial airflow over the ice sheet follows the topography, as seen in the close alignment of snow sastrugi with the katabatic winds. Katabatic winds are important for redistributing snow on the ice sheet, or carrying it off continent, thereby influencing the mass balance. Satellite thermal infrared (IR) images frequently reveal dark plumes emanating from airstream confluence areas around Antarctica associated with the katabatic winds. The warmer radiant temperatures of the plumes likely result from combinations of turbulence, suspended snow, and the compressional warming of sinking air. By contrast, synoptic episodes of high winds from the east or northeast occur as intense depressions impinge upon the coast from the northwest.

Intraseasonally, periods of stronger (weaker) katabatic winds seem to be associated with a shallower (deeper) polar vortex. Accordingly, fluctuations in katabatic winds (e.g., the frequency variations of satellite-detected thermal plumes) have associated distinct large-scale patterns of pressure and height anomalies. A similarity in the temporal scales of katabatic wind fluctuations and the so-called intraseasonal, or "30° to 60-day oscillation," may indicate a physical link between southern high and lower latitudes, at least in the Indian Ocean sector.

Barrier winds. On the western sides of the Weddell and Ross seas, strong and persistent southwest to southerly winds comprise a so-called barrier wind. The barrier wind is explained from thermal wind principles: very cold and stable air over the ice shelf moves westward and is dammed up against the coastline. The very strong temperature gradient that is induced results in southerly flow along the eastern side of the barrier (i.e., the colder air is located on the right). Recent field experiments in the western Weddell Sea suggest a low-level jet structure to the barrier wind when strong surface-based temperature inversions occur.

Barrier winds can be enhanced by synoptic flow when low pressure is located to the eastward or northeastward. The barrier wind combines with the upper-ocean cyclonic gyre to advect sea ice and icebergs equatorward, particularly in the Weddell Sea. This process increases the temperature meridional gradient between the eastern and western Antarctic Peninsula, and ensures that lower temperatures occur, on average, in the southern South Atlantic compared with similar latitudes in the South Pacific.

Mean Sea Level Pressure (MSLP) and Geopotential Heights

Reducing Antarctic surface pressures to mean sea level results in a "glacial anticyclone." However, the high elevations of the ice sheet make this feature somewhat unrealistic, as they extend into the cold-cored circumpolar vortex of low pressure/height. Bordering the continent, the ACT of low pressure comprises the zone of dissipation and stagnation of frontal cyclones that have immigrated from lower latitudes. The time-averaged ACT comprises several well-defined centers of low pressure near the Ross and Weddell seas, and also off Wilkes Land in East Antarctica. It exhibits limited variations in latitude location and intensity between the extreme seasons, but maximum variability occurs in association with the SAO: closer to Antarctica in the equinoctial months, and further equatorward in the solstitial months.

Interannually, there is considerable variability of the MSLP field associated with the ACT, some of which is ENSO-related. In particular, the ASL comprises a "pole of maximum variability" in the SLP field. When the ASL is weaker, often in El Niño years, an intensified low may appear to the westward in longitudes of the Ross Sea.

The meridional strong gradients of temperature evident near the surface relax, on average, in the free atmosphere: contrasting radiation and energy budgets associated with continental ice, sea ice, and ice-free ocean, diminish with altitude. The tropospheric circulation over higher southern latitudes is dominated all year by the circumpolar westerly vortex of low-amplitude wave number one. In contrast, a three-wave pattern is prominent on synoptic time scales, and also during periods of blocking. It comprises troughs over the three major ocean basins, with cyclogenesis and satellite-viewed cloud axes located just to the eastward, and ridges located upstream over Australia, southern Africa and South America.

Winds in the Free Atmosphere

The Southern Hemisphere westerlies comprise the "flywheel" of the atmospheric general circulation, and exhibit little seasonal variation. Over the South Pacific Ocean, ENSO dominates the interannual variability of wind speed in the mid to upper troposphere, as manifest by an out-of-phase association between subtropical and middle to higher latitudes, or "split flow." Thus, in this sector at least, the subtropical jet stream, or STJ (polar front jet stream, or PFJ) tends to be stronger (weaker) during El Niño (La Niña) events. There is evidence that the opposite pattern of tropospheric westerly wind speeds occurs in the South Atlantic; that is, an enhanced STJ there when the South Pacific STJ is weaker, and vice versa.

Synoptic Climatology

The climatology (i.e., mean and variability patterns) of weather systems in the Antarctic involves three main types of system, as follows:

- Synoptic-scale frontal cyclones, originating mostly over lower latitudes;
- Mesoscale cyclones developing in cold-air outbreaks ("polar lows," cold-air mesocyclones) over higher latitudes;
- High pressure ridges interrupting the time-averaged ACT.

Synoptic Cyclone Activity

Synoptic cyclones are significant for coastal Antarctica because of the clouds, precipitation, and strong winds typically associated with these systems on their forward (i.e., eastern, southeastern) side. There, warm air overruns colder air near Earth's surface. However, the influence of these cyclones also is felt in the continental interior, especially West Antarctica, where relatively low ice-sheet elevations permit easier transit of cyclones. Satellite-based studies indicate that cyclogenesis (i.e., the formation of new cyclones) and reintensification of older systems is more common around Antarctica than previously believed. This includes synoptic-scale "bomb" events (i.e., explosively deepening cyclones) that bring extreme weather to coastal Antarctica.

Climatologies of synoptic cyclones over southern higher latitudes have been developed from tracking the associated cloud vortices evident on satellite imagery, and applying cyclone-tracking automated programs to longer-term digital series (e.g., reanalyses) of MSLP. These separate approaches broadly confirm one another in terms of extratropical cyclone frequency mean and variability patterns. Specifically, cyclones develop preferentially over middle latitudes of the ocean basins; South Atlantic, Indian Ocean, and South Pacific. As cyclones mature and intensify, they move to the southeast along well-defined climatic "storm tracks," until merging in the ACT at around 60° S. These storm tracks fluctuate interannually in association with climatic teleconnections such as ENSO, particularly in the Pacific sector of West Antarctica. Cyclonic activity tends to increase (decrease) just west of the Antarctic Peninsula during El Niño (La Niña) events, although this relationship is not unique.

Cold-Air Mesocyclones and "Polar Lows"

The scale of synoptic weather charts and lack of data at mesoscales over the Southern Ocean long precluded an accurate inventory of mesocyclones in the Antarctic and sub-Antarctic. However, polar-orbiter satellite imagery permits the detection and characterization of these systems from their associated smaller-scale cloud vortices. Because mesocyclones develop in cold-air surges, they tend to move to the east and northeast after initiation; away from the continent. Accordingly, the Drake Passage comprises a favored mesocyclone track, enhancing this area's long-held reputation for storminess. Mesocyclones occur preferentially within two main zones of the Antarctic and sub-Antarctic: the SSIZ, especially near the ice-ocean edge; and close to the continental margin, particularly the confluence areas of katabatic winds.

"Synoptic climatologies" of cold-air mesocyclones have been developed for the following areas: the Ross Sea and Ross Ice Shelf, Marie Byrd Land and Siple Coast, the Bellingshausen and Amundsen seas, and the Weddell Sea. These regional preferred locations manifest the dominant physical processes associated with mesocyclogenesis in Antarctica: respectively, baroclinity in the atmospheric boundary layer, associated with strong horizontal gradients of temperature and moisture that result from differential energy fluxes between ice and water; and "column stretching" of air as it descends the ice sheet (i.e., increasing positive vorticity). The latter process sometimes is enhanced by strong latent heating from shore polynyas. The AWS pressure data have indicated mesocyclones developing on parts of the ice sheet and ice shelves that lack a significant cloud vortex. The latter results from combinations of the very dry air, and the difficulty in separating clouds from the ice surface in remotely sensed data.

Mesocyclone climatic variability is both interseasonal, in association with the SAO, and interannual, with an ENSO signature. The SAO is evident from increased frequencies of mesocyclones over the sub-Antarctic in March and September, relative to ocean areas further north. Interannually, an association with ENSO has been identified for the Ross Sea and Bellingshausen-Amundsen sector for the consecutive winters of 1988 (following an El Niño) and 1989 (following a La Niña). Mesocyclone activity was more frequent in the Ross Sea sector in 1988, and more frequent in the Bellingshausen-Amundsen sector in 1989. These variations are consistent with the shifts in atmospheric long waves, patterns of SST anomaly, and sea-ice extent, although additional years should be studied to fully elucidate these polar low relationships.

High Pressure Ridges

The dominance of cyclonic activity in the sub-Antarctic means that high pressure ridging from higher latitudes typically is transient and relatively weak. It is most evident on synoptic (daily) time scales, when the circulation can be much more meridional than that portrayed in time-averaged maps of MSLP. However, anticyclonicity that is sustained over a number of days can occur in association with ridges extending poleward, in the following preferred longitudes: 0° to 15° E, 50° to 60° E, and 140° to 150° E, with weaker ridging at 70° to 90° W. Blocking episodes in longitudes of eastern Australia and the Tasman Sea can deliver significant precipitation to East Antarctica. They are frequent during El Niño events.

Modes of Sea Ice—Atmosphere Coupled Variability

Antarctic sea ice interacts with the overlying atmosphere to manifest circulation variability on temporal scales ranging from the daily through interannual to decadal. Geographically dependent patterns of coupled sea ice—atmospheric circulation variability result from radiative, thermodynamical (e.g., layer thickness) and dynamical (near-surface wind field) processes linking the ice and the air. In particular, ice extent in the Ross and Weddell varies out of phase.

Synoptic interactions occur on daily to weekly time scales and regional to sector spatial scales. They involve the sea-ice edge and encroaching cyclone systems. For example, examination of early satellite passive microwave temporal data showed wavelike features in the Antarctic ice edge ascribed to the effects of synoptic systems. More recent analyses using scatterometer and other data confirm the role of frontal cyclones in the patterns of ice advance and retreat and also ice concentration, including polynyas. Moreover, patterns of cyclonic activity that are sustained on climatic scales (e.g., as "storm tracks" >10 days) similarly are evident in sea-ice extent and concentration regional patterns.

On the forward (i.e., eastern) side of a low, northerly winds advect mild air and cause the ice edge to retreat southward and ice concentrations to increase due to convergence and compaction of the ice. On the back (i.e., western) side of a low, cold-air advection from the south enhances the ice advance through a combination of freeze-up and wind drift of ice towards lower latitudes.

There is no clear statistical association between the zonally averaged Antarctic sea-ice extent and storm tracks, however the changed sea-ice conditions induced by synoptic cyclones can increase cold-air mesocyclogenesis to the westward near the ice edge. Although blocking in the sub-Antarctic climatologically is weaker and of shorter duration than in the Northern Hemisphere it has associated signatures in the regional sea-ice patterns. Blocking leads to regional ice retreat towards the continent and enhanced fluxes of heat from the ocean into the atmosphere. Accordingly, such episodes may intensify storminess in the region once the blocking ridge has broken down.

Monthly to seasonal interactions appear in their coupled wave-number patterns: the locations of anomalous troughs (ridges) in the tropospheric height field tend to coincide with the longitudes of greater (reduced) ice extent. This relationship occurs because cold air advection in the troughs is associated with ice advance, and warm advection and ice retreat occurs in the ridges. Similarly, winters having greater (reduced) sea-ice extent tend to coincide with stronger (weaker) zonal westerlies in the sub-Antarctic, at least, in longitudes of the Ross Sea. This relationship likely comes about because stronger westerlies encourage divergence of the pack, which leads to ice growth through a combination of freezing and equatorward ice advection. There is evidence that an equatorward-displaced sea-ice edge strengthens the latitudinal temperature gradient, further intensifying the zonal westerly wind index.

The dominant SAO of MSLP, height and tropospheric winds is linked to the zonal patterns of ice advance and retreat occurring via the shifts in latitude location of the ACT between equinoctial and solstitial months. Because the ACT represents a tropospheric shear zone between the westerlies (polar easterlies) located to the north (south), its location with respect to the SSIZ influences the ice-edge latitude and ice-water concentration during the year, as follows. In early autumn, the ACT is located equatorwards of the sea ice: ice growth occurs as temperatures fall but is relatively gradual because of compaction due to easterly winds. Ice growth is more rapid after the ice edge moves north of the ACT in late March, and continues through winter because of subfreezing temperatures and the ice divergence induced by westerly winds. In late spring, there is a relatively rapid retreat of the ice through a combination of rising temperatures (i.e., enhances melting) and the northward movement of the ACT (i.e., ice is compacted due to convergence induced by easterly winds).

Interannual Coupled Variations between the sea ice and atmosphere mostly are linked to the dominant circulation teleconnection patterns; notably, ENSO and the Pacific-South America (PSA) pattern. Although details of these teleconnections are given elsewhere in this Encyclopedia, their general associations with Antarctic sea-ice variability are provided here.

The Trans-Polar Index, ENSO, and Antarctic Dipole:

Early studies of the variability patterns of Southern Hemisphere atmospheric circulation from Principal Components Analysis (PCA) showed an out-of-phase relationship of pressure/height between Australia/New Zealand and South America. This teleconnection pattern is described by a Trans-Polar Index (TPI), representing the difference in MSLP monthly anomalies between Hobart and Stanley. Positive (negative) values of the index correspond to an enhanced ridge (trough) in the Australian sector, and an enhanced trough (ridge) over southern South America. Comparisons of TPI with the long-term sea-ice record for Orcadas show a significant association between the two variables: years of more extensive or later clearance of the ice accompany an enhanced trough over the region and greater incidence of southerly winds, and vice versa. Often, the anomalous trough (ridge) in the Weddell Sea sector accompanies an El Niño (La Niña) event. Moreover, ENSO typically has associated sea-ice conditions that are out of phase between the Amundsen-Bellingshausen seas and Weddell Sea. These sea-ice contrasting anomalies across the Antarctic Peninsula also are evident in MSLP and temperature, and statistically are linked to larger-scale variations in SST and surface air temperature in the tropical Pacific and even globally. Accordingly, this Antarctic Dipole Index (ADP) correlates well with the Antarctic sea-ice edge in the Pacific and South Atlantic sectors.

The Antarctic Oscillation (AAO)

The dominant mode of interannual climate variability in the Southern Hemisphere extratropics, or Antarctic Oscillation (AAO)—also known as Southern Annular Mode (SAM) and Zonally Varying Mode—has an association with the zonally averaged sea-ice conditions in the Antarctic: ice is more (less) extensive for stronger (weaker) westerlies. Although this association is consistent with that found regionally and on shorter time scales, there may be a seasonal dependence.

Decade-Scale Coupled Variations—The Antarctic Circumpolar Wave (ACW)

Decadal-scale coupled atmosphere—upper ocean variations, including sea-ice conditions, mostly are connected with the Antarctic Circumpolar Wave (ACW). The ACW evidently is of extratropical origin and, in its purest form, is a wave number 2 pattern of alternating anomalies of high and low atmospheric pressure. In the upper ocean, anomalies of downwelling, reduced salinity and less extensive sea ice result from enhanced northerly winds east of the centers of negative pressure/height anomalies. East of positive SLP/height anomalies (i.e., high pressure ridges), anomalous upwelling, increased salinity and more extensive sea ice accompany the greater frequency of southerly winds. ACW coupled anomalies propagate eastwards in the ACC for a complete circuit of Antarctica in about 8 years, or 4 years per wave. They are most coherent in the Indian Ocean, South Pacific, and southwest Atlantic, where they may help reinforce—and be reinforced by—the anomalies connected with ENSO. However, the ACW expression is not stable even for the contemporary period; thus, the relationships with sea-ice regimes also are expected to vary. Interestingly, an ACW is evident in long-term ice core data from Dronning Maud Land.

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See also **Antarctic Ice Sheet: Definitions and Description; Circumpolar Current, Antarctic; Climate Change; Climate Modelling; Climate Oscillations; Clouds; Dry Valleys; Ice-Core Analysis and Dating Techniques; Ozone and Polar Stratosphere; Pack Ice and Fast Ice;**

Polar Lows and Mesoscale Weather Systems; Polar Mesosphere; Polynyas and Leads in the Southern Ocean; Precipitation; Remote Sensing; Sea Ice: Types and Formations; Synoptic-Scale Weather Systems; Teleconnections; Temperature; Tourism; Wind

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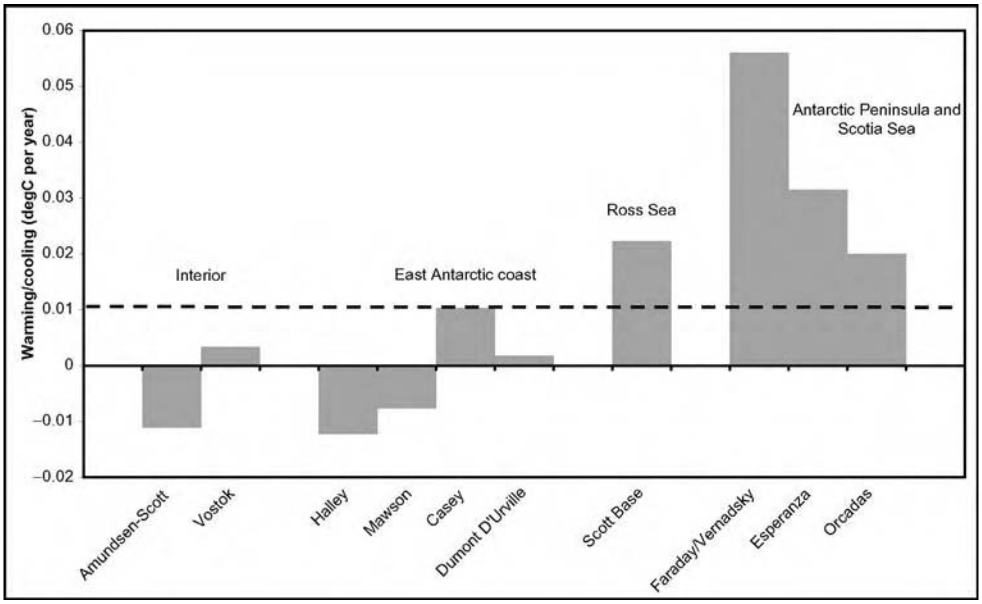
CLIMATE CHANGE

Observations of Recent Climate Change

While the observations made by early expeditions to Antarctica provided a valuable insight into the mean climate of the region, systematic study of the variability of climate at high southern latitudes had to await the establishment of permanent observatories, where long-term climate records could be gathered. The longest such record by far comes from Orcadas station in the South Orkney Islands, established by the Scottish National Antarctic Expedition in 1903 and maintained by the government of Argentina since 1904. A number of stations in the Antarctic Peninsula have unbroken climate records starting in the late 1940s or early 1950s but the majority of records from continental Antarctica start during the International Geophysical Year of 1957/1958. Most of these records are from coastal Antarctica. The only long records from the high plateau of East Antarctica are those from South Pole (Amundsen-Scott) and Vostok stations. The deployment of automatic weather stations and exploitation of remotely sensed data have provided information on year-to-year climate variations in parts of Antarctica remote from the permanent observatories. However, records from these sources are generally too short to provide much useful indication of any long-term changes that may be occurring. A recent development that has proved to be of great value for Antarctic climate studies has been the production of long series of atmospheric reanalyses by the US National Centers for Environmental Prediction and by the European Centre for Medium-range Weather Forecasts. Based around the computer models that are routinely used for numerical weather



Long-term annual mean temperature trends at selected Antarctic stations, grouped by region. All stations shown have records extending back to at least 1958. The record for Orcadas starts in 1903. The horizontal broken line shows the average warming trend for the Southern Hemisphere as a whole over the period from 1951 to 2000.

prediction, the atmospheric reanalyses make use of all available in situ and remotely sensed data to provide a detailed three-dimensional picture of the structure and circulation of the global atmosphere. The reanalyses extend back over 40 or more years but are of questionable accuracy in high southern latitudes before the early 1970s, when satellite data first became available to supplement the sparse observing network over Antarctica and the Southern Ocean.

Analysis of surface temperature records across the Antarctic reveals a complex pattern of variation and change. Around the coast of East Antarctica station records display a mixed pattern of warming and cooling trends. However, none of these trends are statistically significant given the relatively high level of interannual variability apparent in the records. On the East Antarctic Plateau, the record from the South Pole shows cooling in all seasons (statistically significant in the annual mean), while the Vostok record shows little overall change in annual mean temperature. Only in the Antarctic Peninsula is a spatially coherent temperature trend seen. Here, all long-term station records show a significant warming trend in annual average temperatures. The most rapid warming has occurred on the west coast of the peninsula. Annual mean temperatures at Faraday/Vernadsky station have risen by 2.9°C over 1950–1999. This is one of the largest temperature increases seen anywhere on Earth over this period. Warming during the winter (June–August) months (5.5°C over 1950–1999) has made the biggest contribution to the annual mean warming trend at Faraday/Vernadsky but even the smaller warming during summer (December–February, 1.2°C over 1950–1999) is significantly greater than that seen in other parts of Antarctica or across the Southern Hemisphere as a whole. Winter temperatures on the west coast of the peninsula are strongly anticorrelated with the extent of sea ice in the Bellingshausen Sea just west of the peninsula. When the ice edge here is anomalously far north, winter temperatures are below normal and vice versa. As the prevailing winds in the peninsula sector are from the northwest, the sea-ice cover in the Bellingshausen Sea determines how much heat these winds pick up from the ocean. Sea ice thus exerts a strong control on west peninsula temperatures, and the complex interactions between atmosphere, ocean and ice explain much of the climate sensitivity of this region. The Bellingshausen Sea is one of the few sectors of the Antarctic in which sea-ice cover has been observed to decline over recent years and this decline may have contributed to the rapid warming of the west peninsula region during winter.

Effects of Recent Climate Change

The rapid warming of the Antarctic Peninsula has driven significant change in the physical and living environment. In the northern and western parts of the peninsula, mean summer temperatures are close to freezing so even a small temperature increase can greatly increase the number of days on which temperatures rise above freezing and thus cause glaciers, ice caps and ice shelves to melt more rapidly. On the west coast of the peninsula, the area of the Wordie Ice Shelf has decreased from around 2000 km^2 in 1966 to around 500 km^2 in 1992. A similar pattern of ice shelf disintegration has occurred on the eastern side of the peninsula. During the austral summer of 1994–1995, the Larsen-A ice shelf and the small ice shelf in Prince Gustav Channel disintegrated rapidly. The latter event made James Ross Island a true island for the first time since its discovery in 1842, suggesting that recent climate change in the peninsula is exceptional in the context of the historical record. Further south, the Larsen-B ice shelf started retreating in 1998 and underwent a final spectacular collapse in February 2002. While the exact mechanisms responsible for these dramatic changes are still a matter of some debate, it is almost certain that the observed atmospheric warming is the underlying cause. The warming has also driven other slower changes in the glacial environment of the Antarctic Peninsula including the retreat of small ice caps on low-lying islands and a reduction in the area of perennial snowcover in the coastal regions. While less dramatic than the rapid collapse of the ice shelves, these changes have provided increased opportunity for colonisation by plants. The amount of Antarctic hair grass *(Deschampsia antarctica)* on the Argentine Islands increased twenty-five-fold between 1964 and 1990. There have also been large shifts in the marine ecosystem associated with the reduction in sea-ice cover in the Bellingshausen Sea that has accompanied the warming of the peninsula. Numbers of Adélie penguins, a species associated with the sea-ice edge, have declined significantly while populations of chinstrap and gentoo penguins, which feed in open water, have increased.

Outside the Antarctic Peninsula, Antarctic climate has been relatively stable over the period of the instrumental record and the impacts of any changes and variations have been correspondingly smaller. Summer temperatures over the major ice shelves (Ross and Filchner-Ronne) have remained well below freezing, protecting them from the changes seen in the warmer environment of the peninsula. Certain Antarctic environments appear to be particularly sensitive to climate change. For example, the thickness of perennial ice cover on lakes in the McMurdo Dry Valleys appears to have varied considerably in response to variations in regional temperature and precipitation.

Atmospheric Circulation Variability

Studies using atmospheric reanalyses have demonstrated that much Antarctic climate variability is associated with hemispheric-scale patterns (or "modes") of atmospheric circulation variability. The Pacific–South American (PSA) mode is a pattern that links atmospheric conditions over the tropical Pacific with those over the Amundsen and Bellingshausen Seas. This pattern is often particularly strong during El Niño warm events (periods of anomalously warm sea surface temperature in the tropical central Pacific). During an El Niño warm event, atmospheric pressure over the Amundsen and Bellingshausen seas is often anomalously high, leading to a reduction in the strength of the prevailing northwesterly winds along the west coast of the peninsula. El Niño warm events are thus generally associated with colder than average temperatures in this region, with anomalously extensive sea ice. The opposite phase of El Niño (sometimes referred to as La Niña, in which sea surface temperatures in the tropical central Pacific are anomalously cool) often generates an opposite response—anomalously low pressures over the Amundsen and Bellingshausen seas, leading to warmer than average temperatures on the peninsula. Atmospheric circulation changes associated with variations in the PSA pattern also cause significant changes in the rate of snowfall over parts of West Antarctica. It is thus becoming clear that some of the variability observed in Antarctic climate may be attributed to changes in the climate system remote from Antarctica.

While the PSA pattern impacts principally on the climate of the Antarctic Peninsula and West Antarctica, the Southern Hemisphere Annular Mode (SAM, sometimes also called the Antarctic Oscillation, AAO) influences climate throughout high southern latitudes. The SAM is characterised by synchronous atmospheric pressure variations of opposite signs in high- and midlatitudes of the Southern Hemisphere. These cause strengthening or weakening of the circumpolar westerly winds that blow around Antarctica. Variability associated with the SAM occurs on timescales from weeks to decades and explains much of the variation in the circulation of the Southern Hemisphere atmosphere. The high index (strong westerlies) phase of the SAM is associated with anomalously warm conditions over the Antarctic Peninsula and anomalously cool conditions over much of the rest of Antarctica. An opposite response is seen when the SAM is in its negative phase (weak westerlies). Variations in the SAM also generate variability in the Southern Ocean, since the westerly winds are the principal driving force for the Antarctic Circumpolar Current. Observations suggest that the SAM has tended towards a more positive phase since the mid-1960s, leading to a 15%–20% strengthening of the circumpolar westerly winds over this period. This trend in the SAM is consistent with the pattern of temperature change seen over this period—warming in the Antarctic Peninsula and cooling over the East Antarctic Plateau. There is still debate over what has caused the trend in the SAM. Experiments with global climate models suggest that increases in greenhouse gasses, such as carbon dioxide, as a result of human activity, will lead to a strengthening of the circumpolar westerlies. However, the phase of the SAM appears to be influenced by a number of other factors, including levels of ozone in the stratosphere. Depletion of stratospheric ozone since the early 1970s (the "Antarctic ozone hole") may also have contributed to the observed trend in the phase of the SAM.

Future Antarctic Climates

There are considerable uncertainties associated with predictions of future climates. A range of climate models may predict different responses to the same changes in forcing as a result of their representing key processes in different ways. Furthermore, there is a large range of plausible future scenarios for changes in the levels of atmospheric greenhouse gases and other forcing factors. Even at a global level, these two sets of uncertainties combine to give a wide range of plausible future climates while, on the scale of a region such as Antarctica, the uncertainties are even higher. The Intergovernmental Panel on Climate Change (IPCC) has compared predictions of future climate across a range of models and emission scenarios. This exercise suggests that global annual average temperature in 2100 is likely to be between 1.4°C and 5.8°C above its 1990 value. Most models used by the IPCC also predict that temperature changes over Antarctica will be larger than the change in the global mean. Temperature changes of this magnitude will have significant impact in regions such as the Antarctic Peninsula and parts of the sea-ice zone where mean temperatures are currently close to freezing. However, over much of the continent, where mean temperatures are well below freezing even in summer, this warming will have little impact on the cryosphere. The IPCC models also suggest that precipitation over Antarctica will increase by 5% to 20% over the period 1990–2100 as a result of a more intense hydrological cycle in a warmer climate. The increased accumulation of snow over the interior of the Antarctic ice sheets is likely to more than offset any loss of ice due to increased melting in the coastal regions, leading to a small growth in the mass of the ice sheets over this period. This growth in the Antarctic ice sheets over the coming century will act to reduce the expected rise in global sea level resulting from thermal expansion of the oceans and increased melting of ice caps and glaciers elsewhere.

Experiments with a number of climate models suggest that, in association with the predicted warming over the coming century, there will also be a significant strengthening of the circumpolar westerly winds over the Southern Ocean. An increase in the strength of the westerlies will cause important change in the Southern Ocean, including an acceleration of the Antarctic Circumpolar Current, deepening of the ocean mixed layer and changes in the way that water masses are exchanged between the Southern Ocean and the rest of the global ocean. These changes will undoubtedly have important consequences for marine ecosystems in the Southern Ocean and for the global ocean circulation, but these remain to be properly quantified.

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See also **Climate; Climate Modelling; Climate Oscillations; Ice Shelves; Southern Ocean: Climate Change and Variability; Teleconnections**

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CLIMATE CHANGE BIOLOGY

Climate change biology is the study of the effect of the rate and magnitude of global climate change on living organisms, from cells to ecosystems. Identifying biological responses to climate change involves establishing (1) the likely effects of these changes on species; (2) the capacity and mechanisms by which species respond; and (3) impacts on species interactions and ecosystem processes. Climate change biology in Antarctica is considered particularly important because of the rapid rates of climate change in polar regions, and the sensitivity of communities living at the physiological limits of life-supporting conditions.

Current and predicted climate changes are inconsistent across Antarctica, but include general warming of atmospheric and marine temperatures. Precipitation patterns are changing with an average increase in rainfall on the Antarctic Peninsula and a decline at several sub-Antarctic sites. El Niño Southern Oscillation events, which have significant impacts on the ecology of parts of Antarctica, remain highly unpredictable. Ultraviolet B radiation has increased as a consequence of the spring ozone hole. The direct impact of increased CO_2 on Antarctic ecology is considered to be comparatively limited. However, extremes, daily and annual ranges, rates of change, and the predictability of climate variables are biologically highly significant. The microclimatic conditions to which organisms are exposed, particularly in terrestrial environments, are in some cases also more extreme than coarse climatological readings show. Climate change effects will also differ between Antarctic biogeographical zones, and marine, freshwater, and terrestrial habitats.

Individual species respond differently to climate change; some may benefit while for others the consequences will be negative. All species have both optimal and threshold abiotic environmental limits, some fairly narrow and others broad, beyond which they perform poorly or are unable to survive. Antarctic marine benthic species, for example, have narrow temperature limits, and many are unable to survive temperature increases of even 1°C–2°C. Species responses to suboptimal or sublethal climatic conditions include either adaptation to changing local conditions or tracking optimal climate conditions by a shift in range distribution. Alternatively, local declines in population abundance may result in eventual extinction. Climate may alter, either directly or indirectly, the morphology, physiology, life history, phenology, behaviour, interactions, population dynamics, distribution, and geographic range size of species. At present we have only a fragmentary understanding of the direct, indirect, and interactive effects of different parameters of climate change on species, communities, and ecosystems. This is as true in Antarctica as it is elsewhere. Nonetheless, the fact that climate change is responsible for certain observed phenological, distributional and abundance changes in species is certain.

Antarctic terrestrial fauna and flora are well adapted to survive freezing and subzero temperatures. However, because they evolved under warmer temperatures and more intense ultraviolet radiation conditions, it has been predicted that they will respond positively to projected changes. In terrestrial habitats, climate amelioration (warming, longer growing seasons, and increased water availability) is considered to result in a general, additive increase in the abundance and distribution of plant and animal species, with a slow poleward shift in more temperate conditions and associated ecosystems. As a consequence, Antarctic terrestrial communities will become more productive and more complex. The extreme isolation of much of the Antarctic territory will retard this process. Nonetheless, colonization rates of exotic species in the sub-Antarctic have increased as a consequence of human activity, and milder climates will facilitate the successful establishment and spread of exotic species. Exotic species are also often very responsive to warming and may benefit more from climate amelioration than native species, with potentially significant consequences for the composition and diversity of Antarctic communities.

Retreating glaciers as a consequence of regional warming will result in the expansion of area available to permafrost-associated plant communities. However, changing freeze-thaw cycles may have negative consequences for some soil-dwelling species. Antarctic invertebrates tend to have flexible life histories, and warming will increase metabolic and development rates resulting in shorter generation times, greater abundances, and possibly species range expansion. Significant population expansion has been recorded for the two vascular plant species on continental Antarctica. However, some arthropods are sensitive to drying and a positive population response to warming may be curtailed in regions experiencing a reduction in rainfall. The availability of liquid water is generally more limiting than temperature to many Antarctic microbes, plants, and invertebrates.

Higher temperatures and ice reduction will bring about long-term changes in the physical oceanography and ecology of marine Antarctica. The distribution of sea ice, altered by both warming and cooling, plays an extremely important role in the ecology of the southern ocean. There is a close association between the marginal ice zone and phytoplankton blooms. Changes in the area and latitude of this zone, as well as in ice thickness and light penetration of the water column, alter patterns of primary productivity. Primary productivity in the southern ocean is a major driver of the distribution, reproductive success and population size of primary (such as krill and some fish species) and secondary consumers (birds, predatory fish, and marine mammals).

Ultraviolet B radiation is biologically harmful, and although species responses differ, it inhibits photosynthesis in many autotrophs (algae, cyanobacteria, lichens, bryophytes, and flowering plants). The long-term ecological impact of the increase of UV-B radiation in Antarctica remains uncertain, with only some studies showing a reduction in marine primary productivity, associated with a change in phytoplankton size and community structure. Should the net effect of high UV-B radiation in Antarctica be negative, the results will be far reaching because phytoplankton forms the basis of the marine food web. The interaction between solar radiation and ice extent may also be important, with a reduction in sea ice resulting in increased exposure of marine autotrophs to UV-B radiation. Terrestrial lichens, algae, and vascular plants are considered to be comparatively less susceptible to high UV-B radiation, although increased UV radiation has been associated with reduced growth rate and morphological changes in Antarctic flowering plants.

In summary, major uncertainties remain about the nature, speed, and distribution of climate changes across Antarctica. This makes the widespread prediction of biological responses difficult. Results from single species and single climate change parameter studies must be interpreted with caution, because of the potentially overriding synergistic effects of adaptation, trophic dynamics, and biogeochemical cycling. Nonetheless, there is hard evidence for biological responses to climate change in the region. Therefore, ongoing monitoring of key biotic and abiotic indicators is critical to the management of the consequences of climate change in Antarctica.

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See also **Adaptation and Evolution; Climate Change; Cold Hardiness; Reproduction; Seasonality**

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CLIMATE MODELLING

In many branches of physical sciences understanding the properties and behaviour of systems can be greatly helped by assembling physical models and subjecting these to a range of external forcings of interest. For example, discerning the flow of air and the dispersal of pollutants around cities has in the past been greatly assisted by making physical models of such cities and placing them in wind tunnels. Using the appropriate array of sensors one can then determine the flow patterns and trajectories associated with mean conditions over the city. In the wind tunnel one can also determine the sensitivity of the circulation to, for example, the addition of structures, changes in mean wind speed, changes in the "roughness" of the surface, and low-level vertical stability.

Powerful as this approach is, there are clearly limitations to its applicability to studying global climate and in particular the climate of the Antarctic region. Modern climatology shows that climate must be seen in a global context. The environment of no part of the world can be considered in isolation, and the many regional manifestations of climate must be considered against the background of the largest-scale processes and connections. It is obviously a very challenging problem to represent with a physical model in the laboratory a sphere to which an ocean, atmosphere, cryosphere and biosphere are held in place by gravity! To add to the complexity, the sphere itself is rotating. It is well understood how the rotation of a planet affects its climates, and any such model would have to include this effect. One can readily see that the construction of physical models of a given system is not always a sensible, easy, or even possible way to proceed.

An alternative approach is through the use of *numerical modelling*. Numerical climate models are based on the fundamental laws of physics which govern the physical and chemical properties of all the relevant media, or a simplification of these. Climate scientists use a broad hierarchy of models from the very simplest (for example a model which shows only how the global average surface temperature changes in response to changes in the output of the Sun) to the most complex "General Circulation Models" (GCMs). The simpler models have the advantage of allowing a ready comprehension of the behaviour of the climate system, but have the disadvantage that they are capable of representing the physics only in a reduced or simplified form. By contrast, though many GCMs are now run on PCs or clusters of PCs, GCMs have the drawback that they require massive computer resources (indeed stretching those to their limit), but they encapsulate our best and most comprehensive understanding of the laws of physics. The use of a range of models of different complexities is an invaluable aid in studying climate. We here address climate modelling undertaken with GCMs.

The fundamental equations upon which GCMs are built include Newton's Second Law (which describes how atmospheric wind, ocean currents and glacial ice flow respond to the variety of forces acting on them), the continuity equation (which says that mass must be conserved), and the thermodynamic equation (which tells how the temperature in the atmosphere or ocean will change). In addition, there are basic physical principles which determine the distribution of water vapour in the atmosphere and salt in the ocean and the consequences of those distributions (e.g., precipitation and ocean water mass formation). Depending on the purpose to which a model may be designed, it may also incorporate mathematical equations which represent, for instance, the creation and destruction of stratospheric ozone and the three-dimensional structure of isotopes in the ocean.

The mathematical (differential) equations previously outlined are nonlinear and very complex and cannot be solved with standard mathematical techniques. For this reason they can only effectively be solved on a computer. The first challenge that arises in obtaining such a numerical solution is that the equations are applicable in *continuous* space, whereas computers have a *finite* (albeit large) capacity. One of the consequences of this is that the equations must be solved at a grid of points (or boxes) which are separated by finite distances. Typically the "grid spacing" used in the atmospheric component of global climate models is of the order of about 150 km in the horizontal and a few hundred meters in the vertical. Because neighbouring regions in the atmosphere and ocean communicate with each other, this *discretization* of space means that the horizontal and vertical transmission of information is somewhat distorted. (This distortion is reduced as the grid spacings are decreased. As computers become more powerful they are able to handle higher resolution, and hence can represent the media under consideration with more degrees of freedom.)

From these comments it will be appreciated that the mathematical equations solved in models tell how rapidly the model variables *change* as a response to the disposition of the atmosphere or ocean at a given time. This means that the *time* dimension is as important as the *space* dimensions in understanding weather and climate. Hence, just as three-dimensional space must be approximated in the computer by spatial boxes, so too must time be broken up into small chunks (or "time steps"). The fundamental equations are used to show how, from the global distribution of the basic meteorological and oceanic variables at a given instant, these variables will change over a time step (which is usually of the order of 10 minutes). All the variables are then updated, and the procedure repeated for a second time step, and so on. Hence, running a GCM is a "time marching problem" and such a model would be run for a simulated time which is applicable to the problem being addressed. For example, if one were making predictions of El Niño a model may be run for three years, whereas if it was desired to obtain an outlook on how the deep ocean would respond to increasing concentrations of atmospheric carbon dioxide a simulation of many thousands of years would be appropriate.

Given the immense demands placed on computer capacity by climate models, it is not surprising that the evolution of the climate modelling discipline has matched that of the digital computer. The development of the atmospheric component of the discipline could be thought to start with the work of Smagorinsky (1963) and is now a mature discipline.

There are many processes in the climate system which are poorly understood or which, while of central importance, act on space scales smaller than the grid boxes discussed above. Atmospheric convection is one such process. The typical scale of individual convective cells in the atmosphere is 1–10 km, a scale much smaller than the individual boxes. The effect of convection cannot be ignored, however, because convective overturning is responsible for much of the vertical redistribution of atmospheric heat and moisture. Hence, though they act on a small scale, convective cells have a very significant impact of the large-scale atmospheric and oceanic structure. One of the major challenges in developing and using climate models is to represent the net effect of various small-scale processes. This is the "parameterization" problem whereby the statistical effect of features which cannot be modeled explicitly are represented in terms of what is known (i.e., the large scale distribution of the relevant variables).

Climate models are an invaluable tool in understanding and diagnosing climate behaviour. Before their output can be used with confidence it must be shown that they are capable of reproducing the means and variabilities which are displayed by the real climate. Accordingly, there are many programs directed at verifying the outputs of models. The process of verification is not as easy as it may at first appear. This, in part, is due to the fact that the limited number of climate records provide only an imperfect estimate of the "true" long-term climate structure. For example, a comprehensive picture of the three-dimensional structure of the atmosphere is available for only the last 50 years or so, and the spatial and temporal monitoring of the deep ocean is even less comprehensive. In addition, quality observations of many climate variables are very difficult to obtain (for example, the distribution of precipitation over the Southern Ocean), and hence it is not always clear against what "truth" the models should be appraised.

Most climate models in use are able to simulate present climate with commendable accuracy. As they provide a four-dimensional picture of climate their output may be used to explore the complex relations between climate parameters in locations where the relevant data are difficult or impossible to obtain. One of the other main uses of climate models is in exploring the sensitivity and stability of climate to a range of forcings, both internal or external. In particular, such models may be used to reconstruct climates during periods of interest in the past (for example, the Last Glacial Maximum or the warm period during the mid-Cretaceous) and are able to serve as a framework in which limited amounts of paleoclimate information (e.g., tree rings, pollen distributions, gases in ice cores, isotopes in foraminifera) can be integrated to form a complete picture of conditions at the time. Reliable models are also able to provide forecasts of how future climates may respond to changes in "greenhouse" gases such as carbon dioxide and methane. This use is particularly valuable considering that it is generally recognized that human activities are now modifying climate. Given the immense complexity of the climate system, climate models present the only physically consistent tool with which such scenarios can be assembled.

One of the huge challenges in modelling the climate system (and the Antarctic component of it) is that its numerous components have very different timescales. The time required for equilibration (i.e., the time needed to adjust to a new forcing), differs for the various components. The equilibration times for atmospheric process can be as short as 1 day or less, while those in the deep ocean, the glaciers, and ice sheets are of the order of hundreds of years and longer. Climate studies with models can take the form of "snapshots," where one may consider, say, the deep ocean as unchanging and be interested in how the atmosphere and surface ocean may respond on the short time-scale to some imposed forcing. However, it will not be able to give a perspective on long-term changes. The very slow response of ice masses and the deep ocean means that a fully coupled system takes a great deal of time to come into balance with the forcing, and it is important to have an appreciation of these timescales when one is interpreting the simulations of climate models.

While GCMs are global in compass it is important to realize that if their output in the Antarctic region is to be studied such models must incorporate the processes that are of consequence to that environment. The Antarctic region has some very special characteristics which result from the complex interaction between the atmosphere, ocean, sea ice, ice shelves, and the ice cap. One of these is associated with the height of the Antarctic ice cap which rises to in excess of 4 km. This massif has a significant effect on the atmospheric circulation and must be incorporated correctly into models. In addition, the surface over the continent has a strong temperature inversion much of the time and reaches its strongest in the interior in winter, when the surface temperature is more than 25°C lower than the atmospheric temperature a few hundred meters above the surface. These inversions coupled with the steep Antarctic orography give rise to the very strong downslope (or "katabatic") winds that are a persistent feature of much of the atmospheric climate on coastal Antarctica. Careful attention must be devoted to the representations of the interaction between the atmosphere and the sloping ice surface in models if these effects are to be simulated.

The amount and distribution of sea ice around Antarctica is a key determinant of how the ocean and atmosphere interact. This seasonality of this distribution depends critically on the horizontal transports of ice induced by the mechanical stresses exerted by the atmosphere on the top side of the ice and by the ocean on the bottom. Of similar importance in determining the configuration of ice are the heat fluxes from the atmosphere and ocean. Antarctic sea ice does not assume the form of a spatially continuous blanket of ice. It is subject to many stresses including those associated with the very intense depressions which are found off the Antarctic coast. In addition, the presence of strong and persistent winds over the Southern Ocean means that extreme wave conditions occur at high southern latitudes, and the Southern Ocean is consistently the roughest ocean on Earth. These very active wave fields, in turn, can influence ice conditions far into the pack and can even break up solid ice fields. In addition, the tidal activity in the region is responsible for further stress on the thin skin of ice.

In response to these forcings the sea ice continually fractures. When fractures (or "leads") occur, huge amounts of heat and water vapor are transported from the now exposed (relatively) warm water to the cold atmosphere above. These losses from the ocean encourages rapid refreezing and formation of sea ice. Hence part of the characteristics of the sea ice is the balance of the processes which cause fracturing and refreezing. The net result is that the mean concentration of sea ice is quite low near the ice edge (e.g., 50%), and may still exhibit significant percentages of open water of about 5% in the interior part of the pack. Because of the very large difference between the atmospheric and oceanic temperatures in the sea-ice domain, even small amounts of open water can dramatically affect the interaction between the ocean and atmosphere. State-of-the-art climate models predict the distribution of ice concentration, and can hence represent these physical associations.

Sophisticated GCMs also include predictions of sea-ice thickness. It should be pointed out that when sea ice forms, salt is leached out of the ice and in turn forms a very dense layer just below the ice. This dense layer descends the continental slope and drops into the abyssal waters. This sequence is a major component in the formation of Antarctic Bottom Water, which is a cold dense layer that is found at the bottom of much of the world's oceans, and gives the global ocean many of its special properties. The appropriate representation of these complex processes is critical if the climate of the ocean is to be represented accurately.

The cryosphere is involved in other aspects of climate in the Antarctic region, and one of these is associated with the many ice shelves distributed around the periphery of the continent. Ice shelves are made up of ice which is floating on the ocean's surface, but which is attached (or grounded) to the continent, or fed by processes which are occurring on the continent. As distinct from sea ice (which has a typical thickness in the Antarctic of 2–3 meters) the major ice shelves typically have a thickness of a few hundred meters at their front, and can reach thicknesses of up to 1 km near the coast. Their thickness is so great as to prevent, as distinct from sea ice, any interaction between the atmosphere and ocean. However, their presence significantly affects the local environment. The more comprehensive climate models include representations of these features. Considerable interest centres on their future stability. Numerical models explain how the stresses on ice streams and ice shelves lead to crevassing on the upper surface of the shelves. Any surface meltwater can lead to the downward propagation of these crevasses and a weakening of the entire shelf. The rapid disintegrations of the Larsen A ice shelf (on the eastern side of the Antarctic Peninsula) in the summer of 1995 and of the northern part of Larsen B in summer 2002 were reflections of their weakness. The contents of sea floor sediments indicate that these regions has not been ice free for at least the last few thousand years. Summer surface temperatures in the vicinity have shown a clear warming trend, and the two years referred to above had unusual temperatures of above 0°C. It is believed that the melt waters caused by these above-freezing temperatures were sufficient to trigger the disintegrations. There is also evidence of warm water intrusion at the base of the shelves at the time of the breakup. Comprehensive climate models include representations of the ice shelves and it can be seen as important that this matrix of processes be included in our best models if they are to provide guidance on future changes in this highly complex system.

Another fundamental constituent of the climate system in the Antarctic region is the Antarctic Circumpolar Current (ACC) and the small scale variability it exhibits. The ACC is unique (and of considerable relevance to the disposition of global climate) in that it connects the world's three major ocean basins and that its strong currents extend almost all the way down to the ocean floor. The types of mixing processes occurring in this environment must be properly represented for models to be able to simulate these characteristics. Of importance too is that the oceanic component of models be "eddy resolving." In the global atmosphere the most important scales (the "synoptic scale") are of the order of 1000 km and greater, while in the ocean this scale is much smaller (about 50 km). To represent fully the important transfers that these systems bring about, the model resolution in the ocean should be finer than that discussed above for the atmosphere. It is believed that these small scale eddies play a very significant role in determining the structure of the ACC and of the ocean climate in the Antarctic region.

Ian Simmonds

See also **Antarctic Bottom Water; Antarctic Ice Sheet: Definitions and Description; Atmospheric Boundary Layer; Circumpolar Current, Antarctic; Climate; Climate Change; Climate Oscillations; Glaciers and Ice Streams; Ice Sheet Modeling; Ice Shelves; Ice-Atmosphere Interaction and Near-Surface Processes; Larsen Ice Shelf; Pack Ice and Fast Ice; Paleoclimatology; Polar Lows and Mesoscale Weather Systems; Sea Ice, Weather, and Climate; Southern Ocean; Southern Ocean Circulation: Modeling; Southern Ocean: Climate Change and Variability; Teleconnections; Temperature; Tides and Waves; Weather Forecasting; Wind**

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CLIMATE OSCILLATIONS

Variability in the extratropical circulation of the Southern Hemisphere strongly affects the near surface climate of Antarctica. This is especially true for winter when horizontal and vertical temperature gradients are at their largest; under these conditions, small circulation changes can cause significant temperature changes. A good example is the interaction of the atmosphere with the sea ice edge; sea ice effectively insulates the atmosphere from the relatively warm sea, thereby enabling low air temperatures over the sea ice. If the large-scale circulation is directed off the sea ice, these low temperatures can be maintained and advection of the cold air over the open sea will enhance the formation of new sea ice. When the large-scale circulation is directed from open water towards the sea ice, the opposite will happen.

Climate oscillations (often called climate "modes") are defined and detected as dominant coherent patterns of variability in the large-scale atmospheric circulation. Only recently, several new Southern Hemisphere climate modes have been (re-) discovered or (re-) defined, some of them having a distinct influence on Antarctic near-surface climate. The three most-studied climate modes occurring at high southern latitudes are the Southern Annular Mode (SAM), the Semiannual Oscillation (SAO) and the Antarctic Circumpolar Wave (ACW). These are described in more detail below:

The Southern Annular Mode (SAM), or Antarctic Oscillation, is the Southern Hemisphere counterpart to the Northern Annular Mode (NAM, also known as the Arctic Oscillation). The SAM and NAM describe the temporal strengthening and weakening of the circumpolar westerly winds (polar vortex). Repeated model studies suggest that the SAM and NAM owe their existence to atmospheric processes (i.e., they do not result primarily from ocean-atmosphere interactions). This is confirmed by their typical tropospheric timescale of variability of about 10 days. Moreover, the NAM and SAM are *standing modes* (i.e., they do not travel like the Antarctic Circumpolar Wave) and are called annular (ringlike) or high-latitude modes because their structure extends all the way to the poles and is roughly symmetric around it. Up to now, there is no clear consensus regarding the process that govern the existence of annular modes, apart from the general idea that annular-mode like variability requires wave-induced momentum transport. Another recent observation is that the typical period of variability in the stratosphere is much longer than in the troposphere, and that stratospheric anomalies of annular mode like character propagate downward to the troposphere reaching the surface with a time lag of about 2 months.

Since the 1970s, the SAM (like the NAM) has increasingly been in its positive phase, indicating stronger than average circumpolar westerly winds. In the Northern Hemisphere, this has led to mild winters in Europe and northern Asia. The response in Antarctica has been more complex: East Antarctica has cooled, because a strong and annular vortex decreases air exchange with lower latitudes. It also weakens the katabatic circulation over the East Antarctic ice sheet, which results in decreased downward mixing of warm air and further cooling at the surface. On the other hand, the Antarctic Peninsula and the Weddell Sea experience significant warming when the SAM is in its positive phase. This appears to be a combined result of decreased sea ice cover in the Bellingshausen Sea and weaker cold air advection from the Filchner-Ronne Ice Shelf. This persistent positive phase of the SAM has been tentatively ascribed to springtime ozone loss in the lower stratosphere (the ozone hole); as ozone is depleted, there is less absorption of solar radiation and the lower stratosphere cools which results in anomalously strong westerly winds. However, the greatest change in the SAM has taken place in summer, while the ozone hole is most pronounced in the Antarctic spring. Model studies have also suggested that increased greenhouse gas concentrations would lead to a strengthening of the SAM.

The Semiannual Oscillation (SAO) is the twice-yearly contraction and expansion of the circumpolar pressure trough (CPT). The CPT is a belt of low surface pressure surrounding Antarctica that is dominantly present in climatologies of Southern Hemisphere surface pressure. It owes its existence to midlatitude cyclones that usually end their southeastward journey close to the Antarctic coast in the so-called depression graveyards. These cyclones are best developed in the equinoctial months March and September, when the north-south tropospheric temperature gradients between 50° and 60° S are largest in response to the maximum latitudinal gradient in insolation. This results in a CPT that is deeper and located farther southward in the equinoctial months, while it is less deep and located farther to the north in the months of the summer and winter solstices (January and June). The twice-yearly migration of the CPT between these extreme states constitutes the SAO.

The SAO is driven by solar radiation and therefore has a very stable phase. It strongly influences the climate of coastal Antarctica; at latitudes around 65° S, the half-yearly wave dominates the annual cycle of surface pressure, cloudiness, precipitation and near-surface wind speed, with peaks in March and September. The effect of the SAO on Antarctic temperature is generally more hidden, because summer-winter differences dominate the seasonal cycle of temperature. In conjunction with pressure rises over the three midlatitude continents, the expansion of the CPT in June amplifies the wave-3 pattern in the circulation around Antarctica, increasing air exchange with lower latitudes. In those parts of Antarctica that are situated in the poleward branch of circulation anomalies, this causes a significant reduction or even reversal of the seasonal cooling, with midwinter months June and July often being warmer than those of late spring and early autumn. Admiral Byrd of the US Navy first noted this phenomenon in 1934, when he stayed in a winter base in the interior of the Ross Ice Shelf (described in his epic novel *Alone*).

In contrast to its constant phase, the amplitude of the SAO shows large interannual and decadal variability. A weakening of the SAO since the mid-1970s has led to midwinter cooling in those parts of Antarctica that are most affected by the expansion phase of the SAO. It has been suggested that the SAO has varied in recent decades in opposite phase with the SAM, but evidence remains inconclusive. A significant effect of the SAO does not show up in the climatologies of the Northern Hemisphere; here, the thermal response of the continents to the summer-winter insolation cycle dominate the annual cycle of surface pressure.

The Antarctic Circumpolar Wave (ACW), discovered in 1996, is a climate signal in the ocean–atmosphere system in the Southern Ocean. Unlike the SAM, the ACW represents more of an oceanic feature that strongly influences the atmosphere. It is characterized by a persistent phase relationship between warm (cool) sea surface temperature, negative/positive sea ice anomalies and poleward (equatorward) surface wind anomalies. The ACW has a wave number of two (i.e., there are two large regions of relatively warm water, each 3000 to 6000 km across, separated by two equally large patches of cold water). This pattern propagates eastward at an average speed of 6–8 cm per second, taking approximately 8 years to circle the globe. From a fixed standpoint the ACW-related anomalies thus recur every 4 years.

The amplitude of the ACW is highest between 50° and 60° S, and as such its impact on Antarctic climate is limited to the coastal regions. The strength and pattern of the ACW varies with time (e.g., it was weak during the mid-1990s). Conflicting views exist on how these waves are triggered and maintained. One theory is that the ACW is remotely teleconnected to tropical ENSO events (El Niño Southern Oscillation), while another theory states that the ACW is a self-sustained eastward propagating wave generated locally by an ocean-atmosphere coupling mechanism. Finally, it could be a combination of these two mechanisms. As a persistent mode of variability, the ACW is somewhat out of favour these days; although it was clearly present from about 1985 to 1995, it has not been detected in data before or since, so it could well have been a one-off event when other cycles or forcings came into phase.

Assigning a hierarchy of importance for Antarctic climate to the oscillations described above is not possible without taking into account the time and spatial scale of the selected data. If we regard the period with good data coverage (mid-1950s to present) and the area between 20° S and 90° S, the SAM is the most energetic climate oscillation, followed by the ACW. If only the Southern Ocean is considered (20° S to 60° S), the ACW dominates. Spectra of the amplitude time series for the area between 20° S and 90° S show that for oscillations with a period smaller than 1.5 years the AAO explains five times more variance than the ACW, while the opposite is true for periods longer than about 3 years. For periods in between, both modes explain about an equal amount of variance. The observational time series in the high southern latitudes are often too short (<50 years) to make any firm statements about decadal climate variability.

Detecting and analyzing modes of variability in Antarctic climate requires a multitude of statistical techniques applied to time series of three-dimensional fields of atmospheric variables. The only way to obtain these data is through so-called reanalysis projects, in which state-of-the-art numerical weather prediction models are combined with an as complete as possible compilation of observational data. The most widely used reanalyses data sets have been computed by the National Center for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR), both in the USA, and the European Centre for Medium Range Weather Forecasts (ECMWF). All reanalyses data sets have known problems and inaccuracies, but these generally do not prohibit the detection and quantitative analysis of the large-scale coherent structures described here.

The pronounced warming in the Antarctic Peninsula region of about 1°C per decade during the last 30 years has led to catastrophic disintegration of several of the northerly ice shelves. Sediment cores from the ocean floor show that these ice shelves had been stable for at least several thousands of years, and their breakup has been interpreted as the first clear sign of anthropogenic climate change in Antarctica. Unfortunately, the simultaneous reports about East Antarctic cooling and Antarctic Peninsula warming in high-impact journals have led to much confusion in the media and the public's perception of climate change in Antarctica. With our knowledge of Antarctic climate quickly increasing, climate scientists are now faced with the challenge to distinguish between natural and human-induced climate variability in Antarctica and to report this to the public in a consistent manner.

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See also **Atmospheric Boundary Layer; Climate; Climate Change; Ice Sheet Mass Balance; Ice Shelves; Teleconnections; Temperature**

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CLOTHING

Effective clothing is critical for human survival in Antarctica. Antarctic garments at the start of the twentieth century were made from natural fibres such as cotton, wool, and leather. Burberry gabardine was found to be a useful material for making windproof oversuits that were also lightweight and waterproof and provided mobility in the cold. Gabardine was the preferred choice for most expeditions at the time including the Australasian Antarctic Expedition of 1911–1914 led by Sir Douglas Mawson. This expedition established a base at Cape Denison in Commonwealth Bay, one of the windiest places on Earth where gales can reach 200 mph (322 kph). To work outside, the men had Burberry gabardine helmets and blouses that could be worn as one piece to try to prevent blowing snow from getting underneath. Wolfskin mitts were worn as gauntlets over their Burberry jacket sleeves, and crampons—metal "claws"—were fitted onto the bottom of their finnesko (reindeer skin) boots.

Although designed to insulate, provide mobility, and be windproof, these materials did not allow perspiration to escape from the body or enable the wearer to remove or add insulating layers easily. Gloves and mittens were so cumbersome that it was difficult to make adjustments to clothing and equipment without exposing skin to the elements. These factors contributed to the death of Captain Robert Falcon Scott's party on their return from the attainment of the South Pole in 1912. Unable to adjust their insulating layers under their gabardine suits, their clothing became wet with sweat during the day from the exertion of hauling sledges across the ice. As the moisture froze, the garments ceased to provide insulation. The success of Captain Roald Amundsen, who reached the pole first on 15 December 1911 and returned safely, has been attributed to his expedition's better organisation and preparation. Unlike the British party, the Norwegians wore wolfskin suits, adapted from Inuit clothing, under their gabardine outer layers. Amundsen had also learned from the Inuit that wearing clothing loosely could reduce sweating.

For polar clothing to work effectively it must:

- Keep the body warm, particularly the extremities such as the head, hands, and feet
- Allow the wearer to move freely
- Allow perspiration to disperse away from the body, and
- Be easy to add or remove in response to the environment and the activity of the wearer.

The layer method of dressing is the most effective over a wide range of conditions; the sub-Antarctic is cool and wet whilst the Antarctic continent is dry and very cold. In most circumstances, several layers of lightweight clothes are better than one or two layers of thick, heavy clothes. The layers provide greater flexibility and ventilation while the trapped air acts simultaneously as good insulation against the cold.

The real change in Antarctic clothing occurred in the 1970s, with the appearance of new synthetic materials with water-resistant characteristics such as polypropylene and polytetrafluoroethylene (PTFE). PTFE is a membrane that is both waterproof and breathable due to tiny pores in its structure. The pores are small enough to block water droplets but large enough to allow water vapour molecules from body moisture to escape. Modern polar clothing is now chosen from a wide range of artificial and natural fabrics.

Three main layers are used in polar dressing:

The foundation layer is the layer next to the skin and often referred to as "thermal underwear." Modern garments are generally made from synthetic fibres such as polypropylene. Soft, lightweight, and comfortable, it wicks perspiration away from the skin, retains insulating properties when wet, and dries quickly. Fine wool garments are now being used more as they do not smell as polypropylene does after a few days in the field.

The insulating layer is provided by garments worn over the base layer and can be adjusted to match environmental conditions. Draw cords, collars, and zippers enable the wearer to adjust ventilation according to their activity level. Traditionally, wool and cotton were used but these are now supplemented or substituted with modern materials such as polypropylene "fleece." Although wool is a breathable insulator, polypropylene fibres can be used to weave fabrics that are lighter and more compressible.

The outer layer is most important because it protects the body from the elements. The greater the wind speed, the faster the body loses heat, so the outer layer must at least be windproof while still letting perspiration escape. On the Antarctic continent, where conditions are very cold and dry, these garments do not have to be additionally waterproof. Tightly woven cotton such as ventile, which was developed during the Second World War, is still used because it remains supple at low temperatures and is durable. Natural down, the insulating underfeathers of waterbirds, is also highly effective in dry areas when built into jackets ("parkas"). The feathers trap air, providing a warm, insulating layer without adding too much weight.

On the northern Antarctic Peninsula and sub-Antarctic islands, where weather conditions can be wet, cotton and down would lose their insulating properties. They are substituted for with waterproof and windproof outer garments made from PTFE.

The body naturally constricts blood flow to fingers and toes in response to cold, so these parts are most susceptible to cold-related injuries such as frostnip and frostbite.

Footwear epitomises the variety of Antarctic activities and conditions. Plastic, double-insulated mountaineering boots are used for skiing and mountaineering. Knee-length "mukluks" provide very high thermal insulation in a layered range of materials that are efficient only when used on cold dry snow and that require drying out overnight, often in the apex of a tent. Thigh-length waders have been used on ships and on some Antarctic Peninsula ice shelves in deep, wet, soft snow in the austral summer. Gumboots and Sorrels are also worn in warmer and snow-free conditions.

Socks made with wool or with a high wool content are still used and woven using a loop stitch, which is warm, is effective at moving moisture away from the skin, and provides cushioning.

Gloves also vary with environmental conditions and work undertaken. Leather work gloves may be used on research stations. In the field, thin woollen or polypropylene gloves under windproof polypropylene/PTFE overmittens enable the wearer to retain dexterity without exposing skin to the cold. Fleece-lined gloves can be waterproofed with the plastic polyvinyl chloride (PVC), for working with wildlife or fresh/sea water. Freezer gloves with or without polypro gloves are also sometimes used (e.g., for driving zodiacs).

Headwear can be made of natural or synthetic materials and generally consists of a hat, balaclava or face mask, and a neck tube. In extremely cold environments, hats made with natural fur are effective, though fur lining is not very effective in wet conditions. Glacier goggles or sunglasses are used to protect eyes from blowing snow and glare (albedo), which without protection can lead to snow blindness.

Modern Antarctic research stations and ships are well insulated with 24-hour power enabling personnel to work or relax indoors in casual clothing such as jeans and sweatshirts. In laboratories, kitchens and plant rooms, appropriate safety clothing is worn. External doors usually open into a heated room where boots and outer layer clothing or insulated overalls are kept for outside work.

Antarctic programmes often discuss clothing development issues with vendors, but most items are mass-produced and publicly available. Experienced staff test new products in Antarctica and personnel on research stations provide feedback on their clothing and equipment.

AMANDA LYNNES

See also **British Antarctic *(Terra Nova)* Expedition (1910–1913); Heath Care and Medicine; Living in a Cold Climate; Scott, Robert Falcon; Temperature**

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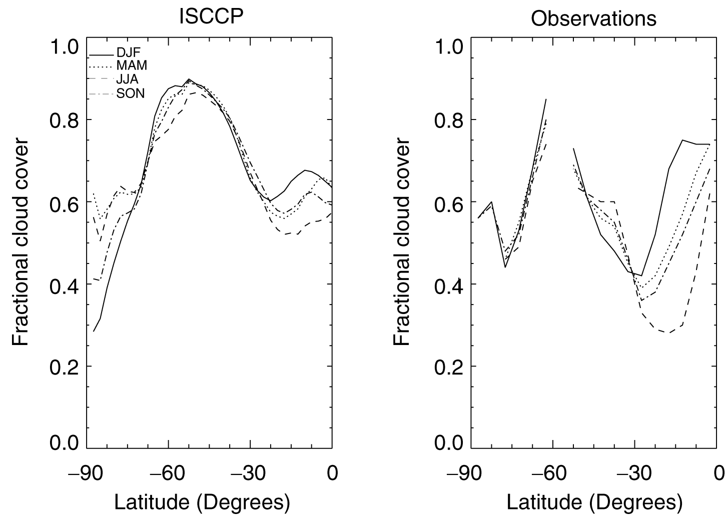
CLOUDS

Cloud Cover

The cloud cover over the oceans that surround the Antarctic continent between 45° and 60° S is generally high, the average being close to 90% in all seasons. Towards the interior of the continent the cloud cover drops to nearer 50%. The latitudinal variations in cloud cover are similar between the two plots, with a maximum in the amount of cloud close to the coast of the Antarctic continent at around 55°–60° S. However the coastal maximum extends further north in the satellite observations to around 45° S. Over the oceans that surround Antarctica there are very few synoptic observations and in this area the satellite observations are likely to be more accurate. In the coastal area, stratocumulus is the predominant cloud type while further inland more high cloud is found.

Ground-based observations of cloud amount and height are particularly difficult to make in the Antarctic environment. Flat featureless expanses of ice make the estimation of height difficult at many surface stations, and during the polar night human observers at all stations find cloud observations difficult. There are also problems with satellite observations of clouds over a snow and ice surface. During the polar day the satellite instruments must distinguish between clouds and a snow surface of similar temperature and albedo,



Zonally averaged total cloud amount from ISCCP satellite retrievals and surface observations for the four seasons.

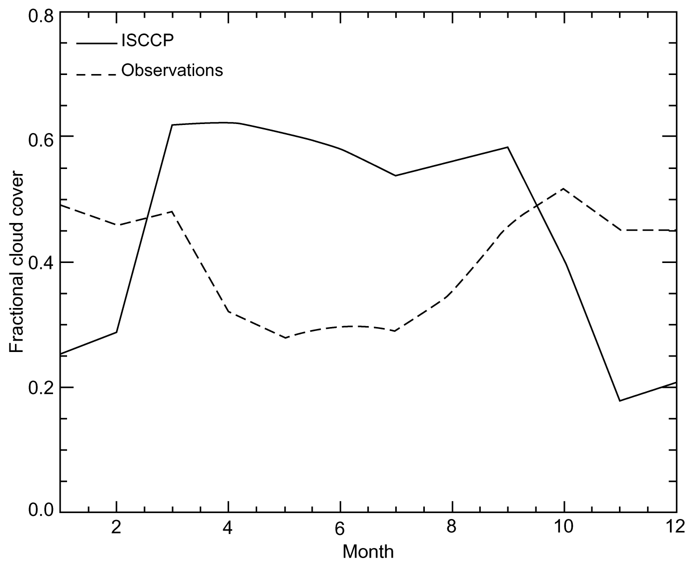
while during the polar night the persistent near-surface temperature inversion raises the temperature of some of the clouds above the surface temperature, making them easier to detect. The surface visual observations of the clouds are likely to be better during the day when the clouds are better illuminated. This means that the average total cloud amount over the polar plateau is around 50%–60%, and probably does not vary much between summer and winter. This also illustrates the problems with observing clouds over the Antarctic.

Microphysical Properties

A few *in situ* measurements have been made in Antarctic clouds and these together with ground-based instrumentation give some information on microphysical properties of Antarctic clouds. These observations have been taken for relatively short periods (one year or less) at a relatively small number of stations, and some care must be taken in extrapolating theses results to the whole of the Antarctic.

Measurements taken at Palmer Station on the western coast of the Antarctic Peninsula indicate that the aerosol concentrations in the coastal regions are lower than in any other maritime region. The long distance between Antarctica and the closest continent mean that the transport of anthropogenic aerosols is minimised. However, measurements on or close to the ground at high altitude coastal sites near the Antarctic Peninsula of ice nuclei revealed concentrations that were orders of magnitude greater than would be expected at midlatitudes. Ice nuclei numbers as high as 2000 L^{-1} were measured with an ice nuclei counter on the Bryan coast at the base of the peninsula. At the same time large numbers of ice crystals (up to 100 L^{-1}) were recorded. Also high numbers of ice crystals have been recorded on the Avery Plateau high on the spine of the Antarctic Peninsula. These measurements of ice nuclei and ice crystals were measured very close to the ground and may not be representative of higher in the atmosphere. Clouds measured from Palmer station had an optical depth of around 7 with a liquid water content of 0.06–0.18 gm^{-3}. The distribution of droplet effective radius measured at Palmer station had a peak at around 5–10 μm.

Measurements at the South Pole using an infrared Fourier transform interferometer revealed clouds that were optically thinner than those found near the coast with optical depths of less than 1. Although the clouds on the polar plateau were optically thin they were often up to 3 km in depth. A bimodal distribution on cloud height is found with peaks in cloud base height close to the ground and at around 2.5 km. The droplet effective radius had a median value of 15.2 μm, but tended to be smaller during the winter. The same pattern was observed in falling snow crystals, with smaller crystals being observed during the winter. During the winter all clouds at the South Pole are likely to be made up solely of ice crystals, although the total ice content is small (a maximum of 0.006 gm^{-3}) compared to midlatitude clouds and to the amount of liquid water found in Antarctic coastal clouds. However, direct sampling of summer cloud particles at the South Pole has found several examples of clouds consisting almost entirely of water droplets at a temperature of –25°C to –35°C.



Monthly total cloud amount at the South Pole from ISCCP satellite retrievals and surface observations.

Clouds and Climate

Clouds play a major role in forcing the climate system as they have a major effect on the radiation balance of the atmosphere. In Antarctica the phase (whether it is composed of ice particles, water droplets, or both) can make a large change to the radiation balance. Modelling studies have shown that changing the phase of Antarctic clouds can have a global effect. However, the present knowledge of microphysical properties of Antarctic clouds makes the parameterisation of these clouds in models difficult. For example, clouds made up exclusively of water droplets have been reported at the South Pole while at the coast, at higher temperatures, clouds consisting totally of ice particles are found (see previous discussion). More work needs to be carried out on the climatology of the microphysical properties of Antarctic clouds, but fortunately the latest generation of space-borne active instruments, such as lidars, hold the promise of producing such climatologies.

Clouds in the Upper Atmosphere

The clouds discussed so far are those occurring in the troposphere; however there are clouds that occur above the tropopause in the stratosphere and mesosphere. In the stratosphere polar stratospheric clouds (PSCs) can form when the temperature falls below 195 K, which can happen during the Antarctic winter. Two types of PSCs can form; type 1 are believed to be formed out of a mixture of nitric acid and water, while type 2 PSCs are less common and are formed of water ice crystals at a lower temperature (188 K). PSCs play a major role in the formation of the Antarctic ozone hole. PSCs are often called mother-of-pearl or nacreous clouds and can be observed from many sites in Antarctica during winter and spring. PSCs may appear similar to cirrus during the day but at sunset all the colours of the rainbow appear.

Polar mesospheric clouds, or noctilucent clouds, form higher in the atmosphere, in the mesosphere at around 85 km. These clouds are sometimes observed illuminated just after sunset.

Tom Lachlan-Cope

See also **Amundsen-Scott Station; Climate; Climate Modelling; Earth System, Antarctica as Part of; Ice Chemistry; Ozone and the Polar Stratosphere; Temperature**

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COAL, OIL, AND GAS

Terra Australis Incognita was a canvas for human wishes, but the fantasies of lush forests, exotic tribes, and fantastic beasts fell to real exploration. Only the supposed mineral wealth of the continent remained, fuelled by a desire to see Eldorado in every unexplored space. Most contemporary comment on the energy mineral potential of the continent has changed little from those old cartographers, with no real basis in scientific reality. The potential for energy minerals (coal, oil, and gas) in Antarctica is extremely low.

Coal, oil, and gas are found on every continent, so it is reasonable to expect that they could be found in Antarctica. However, two areas are debated: the extent of any such deposits, and whether or not anyone has a serious intention to explore for and ultimately exploit them. There was a similar debate on Antarctic minerals, especially during the Convention on the Regulation of Antarctic Mineral Resource Activities (CRAMRA) negotiations. Most of the debate was ill informed, misusing the terms "reserves" and "resources" (Willan et al. 1990).

Of the three sources of mineral energy, coal deposits are easiest to find, to be defined by size and quality, and to exploit. Frank Wild and Ernest Shackleton found the first coal in Antarctica at the head of the Beardmore Glacier (Shackleton 1909). This discovery had enormous significance, as clear evidence that Antarctica had not always been a frozen continent. Subsequent expeditions to the Transantarctic Mountains in the Ross Sea sector confirmed that coal of Permian age (laid down about 255–245 Ma) was present throughout the range. There were also some thinner coals of Triassic age (about 220–230 million years old). The first serious suggestion for mining this came in an exchange of letters in *Time* magazine in July–August 1939. The last piece of the jigsaw was the discovery of coal in the Theron Mountains by Vivian Fuchs in 1956 (Fuchs and Hillary 1958) and in the Amery Oasis area of the Prince Charles Mountains by geologists of the Australian Antarctic Division in the mid-1950s (McLoughlin and Drinnan 1997).

All Antarctic coal lies in a narrow belt between the Weddell and Ross seas and in an isolated patch in East Antarctica; all is of Permo-Triassic age. What is more interesting is what is missing: there are no coals of Carboniferous age (which are the most important worldwide), and none of Cretaceous or Jurassic age (as in the other Gondwana continents). Why? In part, the answer is past climate; Antarctica has been in high latitudes for most of the past 300 million years, and was glaciated during the Carboniferous age. Tectonics are also important. Most of the Cretaceous basins lie within the Pacific margin active belt: sedimentation rates are high and there was much volcanism, preventing coal formation (Macdonald and Francis 1990). The only Cretaceous coals are rare, thin (a few centimetres thick), and discontinuous.

The only Antarctic coals that could be considered exploitable are Permian. Rose and McElroy (1987) showed that they had a high ash and mineral content, and many seams had been metamorphosed by the extensive magmatic intrusions of the Jurassic Ferrar dolerites. Because of the flat-lying stratigraphy of the Transantarctic Mountians, most of the outcrops of Permian coal are at altitudes above 2500 m. These factors, coupled with remoteness of most of the outcrop, and the very large stocks remaining elsewhere in the world, make it impossible to contemplate anyone ever exploiting Antarctic coal, even if they were free to do so.

The case of oil and gas is much simpler: none has ever been found, and beyond desktop studies, there has been no serious attempt to look for hydrocarbons. There are four ways to conduct petroleum exploration; all concentrate exclusively on the sedimentary basins where oil and gas are found. First, look for oil seeps at the surface. This is the way that most of the world's major petroleum provinces, including the Alaskan North Slope, came to the attention of the oil industry. No seeps have been found in Antarctica. Second, calculate the volume of sediment in Antarctic sedimentary basins and multiply that by a worldwide "finding factor" (volume of recoverable hydrocarbons per km^3 of sedimentary rock). St. John (1986) used this approach to suggest that there were potentially 106 billion barrels of oil recoverable in Antarctica (approximately twice the ultimate recovery from the North Sea). This is the highest figure ever suggested for the petroleum potential of Antarctica, and is greatly exaggerated, as the finding factor is skewed by highly productive regions of the Northern Hemisphere. Third, consider the geological evidence for the various elements of the petroleum system: source, maturation, reservoir, seal, and trap. This focuses attention on the Ross and Weddell seas, which are the only areas where basins are extensive enough to host large accumulations of oil or gas. Macdonald et al. (1988) and Macdonald and Butterworth (1990) used this approach to consider the basins around the Antarctic Peninsula; they concluded that there was some petroleum potential in the Larsen Basin, east of the peninsula, but that it was not high. Fourth, go and look for suitable traps with seismic surveys, then drill them. This is a very expensive process: seismic lines are spaced 500 m apart and surveys cost many millions of dollars; wells penetrate to depths of 2–3.5 km and cost tens of millions of dollars. As far as can be ascertained, all seismic surveys conducted offshore Antarctica have been for scientific purposes; the most detailed has a mean line spacing of more than 5 km. The deepest series of boreholes (MSSTS, CIROS, Cape Roberts) have an aggregate depth of only 1500 m (Davey et al. 2001).

In conclusion: No serious oil or gas exploration has been conducted around the continent; likely areas are restricted to the Ross and Weddell embayments; the petroleum potential is unproven (but likely to be low). Coupled with the difficulties of working in the harsh environment, it is unlikely that any exploration will occur in the future.

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See also **Convention on the Regulation of Antarctic Mineral Resource Activities (CRAMRA); Fossils, Plant; Gondwana; Shackleton, Ernest; Transantarctic Mountains, Geology of; Wild, Frank**

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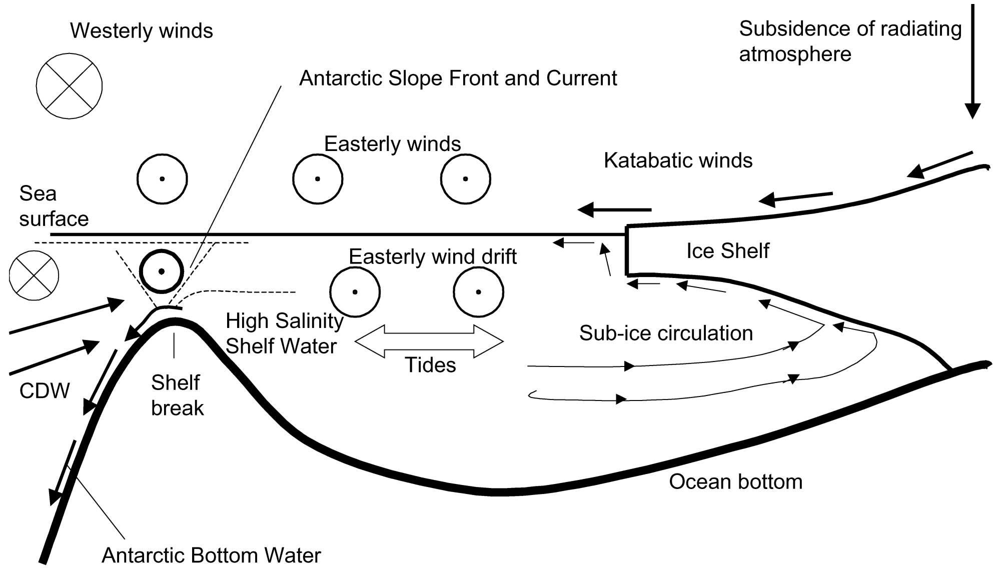
COASTAL OCEAN CURRENTS

The coastal current system around Antarctica is controlled by the interactions with the Antarctic Circumpolar Current (ACC) in deep water to the north, the bottom topography of the coastal region, and the atmosphere—the local winds and the massive seasonal variation in surface heat flux. Antarctica has a long coastline, and the observations of its coastal and regional currents are sparse, mostly confined to summer except for a few long-term moorings, and concentrated in particular areas such as the Ross and Weddell seas. Many regional anomalies, known and unknown, are omitted from this overall picture.

Like most other coastlines, Antarctica has a continental shelf and continental slope, bordering the deep Southern Ocean. However, the continental shelf is much deeper (400–600 m) here than in most other oceans (<100 m), and in many places it deepens toward the coastline, with a sill of about 450 m depth at its outer edge (the shelf break). This unusual depth is attributed to the weight of ice on the continent, depressing the ground beneath. Further offshore, the continental slope to the deep ocean is steepest in the upper 2 km, with typical slopes of 3°–6°, similar to those seen around other continents. Smaller-scale variations on this general topographic pattern include banks and troughs on the shelf, and submarine canyons on the slope and rise, which can help to drain dense fluid from depressions on the shelf out to the deep sea.

North of the continental slope, although it is a notoriously stormy environment, the average wind and its stress on the ocean are eastward. This implies that transport in the surface "Ekman" layer is predominantly toward the north. To conserve mass, the column of ocean water below the Ekman layer rises as it moves southward. This Circumpolar Deep Water (CDW) has been in the deep ocean for a long time (~1000 years), and is relatively warm, salty, low in oxygen, and rich in nutrients compared with the Antarctic coastal environment.

The coastal wind system is quite different from that over the deep ocean. The persistent clear sky over higher ice sheet elevations means that the local atmosphere continuously loses heat by radiation, causing it to steadily subside to the surface. This cold air drains off the elevated continent in all directions in a boundary layer ~200 m thick, in a flow known as a katabatic



Schematic of a north–south vertical section showing some of the aspects of Antarctic coastal currents described. Dashed lines denote isopycnals, and arrows denote wind and current direction. (CDW, Circumpolar Deep Water.)

wind. As this cold flow approaches the coast, the topographic gradient steepens, wind speed increases, and the airflow is channelled preferentially into valleys where speeds of over 200 m sec^{-1} are not uncommon—the strongest winds on Earth. This process continues throughout the year, but is strongest in winter. On reaching a level surface over the ice or water this cold dense airstream thickens and decreases in speed, often through the mechanism of a hydraulic jump. Where topographic channelling is not important, as at low levels over the continental shelf, northward moving air is directed toward the west by the Coriolis force.

At upper levels in the troposphere the wind is predominantly toward the east, circling the Antarctic continent. The two main embayments, the Weddell and Ross seas, are sheltered from this westerly wind stream by the mountains of the Antarctic Peninsula and Victoria Land. These barriers direct the main topographic air streams around them to the north, where each flow separates from the barrier, leaving a large recirculating clockwise eddy in the lee. The wind stress associated with each of these eddies then drives a corresponding clockwise oceanic gyre in the Weddell and Ross Sea basins. These gyres dominate the mean circulation in each basin and have diameters on the order of 2000 km, although the Weddell Gyre is elongated towards the northeast, extending as far as 30° E. Surface current speeds in these gyres are of the of order 10 cm sec^{-1}. At deeper levels in the Weddell Sea, two smaller gyres are evident, one on each side of 15° W. There is also some evidence that the circulation in the Ross Sea below the mixed layer is also made up of three smaller gyres. A wind-generated gyre is also expected in the Prydz Bay region, but it would likely be weaker and on a smaller scale than those in the Weddell and Ross seas.

Air draining off the continent is considerably colder than the surrounding ocean, particularly in winter. In consequence, the ocean loses heat to the atmosphere and freezes to form pack ice. This causes an enormous seasonal variation in the extent of pack ice, which retreats to somewhere near the edge of the continental shelf in summer, reaching a minimum in February. It then extends rapidly northward in autumn and winter due to the decreasing temperature, particularly in the Weddell Sea, usually reaching a maximum extent and thickness in September. The associated surface cooling causes the water over the shelf to be well mixed, particularly in coastal regions where the katabatic winds are strong, generating open areas with little or no ice (such areas are termed "polynyas"). Such regions act as continuous sources of dense salty water because of brine rejection from the continuously forming sea ice. This environment is also affected by CDW that is modified by mixing with Antarctic Surface Water. These and other water masses are identifiable by temperature and salinity characteristics, but the overall seawater density variations over the shelf remain weak.

Wind-driven currents over the continental shelf are thus expected to be largely barotropic, meaning they do not vary much in the vertical, have a simple structure, and are not particularly strong. The prevailing easterly winds produce the observed westward "East Wind Drift" that is prevalent around most of the continent and turns northward along the western coasts of the Ross and Weddell seas. The southward Ekman transport due to this wind tends to cause downwelling at the coast, which also helps to keep the shelf water homogeneous. The East Wind Drift is weaker in winter, when the ice cover resists wind-driven motion. Between the coastal easterly wind regime with southward transport and the ACC to the north with northward transport lies a broad region of surface divergence. This is the main driver for the rising of CDW over the slope and onto the shelf at most longitudes.

In most coastal environments around the world, the main currents are situated over the continental slope. A westward "Polar Slope Current" has been observed in the lower part of the water column north of the South Shetland Islands near the tip of the Antarctic Peninsula, and at several other locations along the continental margin. The natural horizontal scale for deep water currents—the Rossby deformation radius $R_0 = NH/f$, where H is the vertical scale ($\leq$depth of ocean), N the buoyancy frequency of the density stratification, and f is the magnitude of the Coriolis frequency—is only about 12 km in these polar latitudes because of the weak density stratification and large f. Hence there may be significant motion over the slope on these relatively small scales near the bottom or near the surface, including eddies. Tidal currents are strong at a few locations, particularly near the continental shelf break in the Ross Sea and near the Ronne Ice Shelf front.

Near the edge of the continental shelf, CDW over the slope meets the generally denser shelf waters at what has been called the Antarctic Slope Front. The shelf waters have been affected by surface cooling and the addition of brine from sea-ice formation and, along with shallower, fresher source waters, set up a westward "geostrophic" current along the shelf break. This semipermanent feature is narrow, with a typical width <50 km and current speeds of order 10–30 cm sec^{-1}, with little or no signal in the surface layer. The Antarctic Slope Front appears to be present at most longitudes, but is weak or absent from the Drake Passage to 130° W, that is, in the Amundsen and Bellingshausen seas west of the Antarctic Peninsula. Along the shelf break across the Weddell and Ross seas, this front develops a V-shaped profile, a feature that becomes progressively stronger from east to west across each sea. In this flow the isopycnals (lines of equal density) are depressed downward over the shelf break, and current transport is mainly in the relatively fresh water inside the V.

Antarctic Bottom Water is produced by the mixing of dense, cold, high-salinity shelf waters; CDW; and fresher water near the shelf break at the base of the V along the Antarctic Slope Front. This mixing process produces denser water than in the deep Southern Ocean to the north, and it descends the continental slope in substantial quantities. This process is best documented in the Weddell and Ross seas, but also occurs seaward of the Adelie Depression near 145° E, and possibly to a lesser extent in Prydz Bay. In the Weddell and Ross seas, this dense water is formed during most of the year, and may descend the slope as intermittent plumes or as a broad continuous sheet. Water mainly leaks out of the Adelie Depression through submarine canyons. The bottom boundary layer thickness and current dynamics are controlled by a combination of buoyancy, bottom drag, bottom slope, and flow rate. In many regions, details of the bottom topography are not yet well known because of the nearly continuous ice cover, making it difficult to assess the role of bottom roughness, from minor rills to major canyons, in the current structure.

A different type of current is the circulation driven by melting underneath the ice shelves. At most longitudes around the continent, ice is slowly pushed off the land, forming ice shelves hundreds of metres thick that float on the water, extending seaward from the grounding line for distances ranging from tens to thousands of kilometers. Warm salty CDW and cold salty shelf waters flow southward at depth, and melt some of the undersides of the ice shelves, producing cooler, fresher, more buoyant water that rises up along the sloping bottoms of the ice shelves. Although the magnitude of these circulations may be measured in Sverdrups (10^6 m^3 sec^{-1}), the inflowing and outflowing currents only average a few cm sec^{-1}. Also associated with melting and upwelling is a relatively narrow (<20 km) and strong surface current that tracks portions of the coastline. The continuity of this coastal current, in effect an intensified east wind drift, is unknown, but speeds of 20 to >50 cm/sec have been estimated at some locations.

Peter G. Baines

See also **Antarctic Bottom Water; Antarctic Divergence; Antarctic Surface Water; Circumpolar Deep Water; Continental Shelves and Slopes; Ice Shelves; Ross Sea, Oceanography of; Tides and Waves; Weddell, Ross, and Other Polar Gyres; Weddell Sea, Oceanography of**

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COLD HARDINESS

Cold hardiness is the ability of animals and plants to survive subzero temperatures. Subzero temperatures can damage organisms through direct mechanical injury via the formation of internal ice, as well as through conformational changes in membranes and proteins. Antarctic marine and terrestrial organisms must survive very different thermal regimes, and thus have different strategies to survive low temperatures. Internal ice formation is the key issue for any Antarctic organism, which may tolerate the formation of ice in the tissues (freeze tolerance) or avoid the formation of ice altogether (freeze avoidance). Freeze-avoiding species can supercool (keep body fluids liquid at temperatures below the melting point) by the production of antifreezes (any substance which acts to prevent ice formation) and/or by neutralising ice nucleators (any substance that provides a substrate for ice formation). Ice crystals are the best possible nucleator, although other crystals, proteins and some microorganisms also nucleate ice effectively. Antifreezes may act colligatively (in proportion to their concentration, for example salts or sugars) or noncolligatively (out of proportion to their concentration, for example, antifreeze proteins that act directly on ice crystal growth).

Antarctic marine animals inhabit a thermally stable environment—in the presence of sea ice, seawater may be a constant –1.86°C. The intertidal limpet *Patinigera polaris* is exposed to air temperatures which are much lower than seawater temperatures. This freeze-avoiding species relies upon a thick layer of mucus to prevent nucleation by the surrounding ice. By contrast, the blood of most Antarctic fishes is less concentrated than seawater. Fishes risk freezing at ambient subzero seawater temperatures, particularly because of the presence of small ice crystals, both in the water column and in their food. In most species, nucleation by ice crystals is prevented by the production of one or more antifreeze proteins (AFPs). AFPs are present in the tissues, circulate in the blood and are secreted into the gut to act directly on small ice crystals, preventing their growth and the consequent freezing of the fish.

By contrast with marine environments, temperatures in terrestrial environments, and more specifically the surface microhabitats occupied by organisms, may span more than 60°C, with daily fluctuations of more than 30°C caused by solar radiation. Semiaquatic, freshwater species, like nematodes and tardigrades, which live in freshwater streamlets, and semiterrestrial larvae of the wingless midge *Belgica antarctica* must therefore survive an environment surrounded by ice. *B. antarctica* survives these conditions by being freeze tolerant—it can survive the formation of ice inside its body compartments. *Panagrolaimus davidi,* an Antarctic nematode worm from Ross Island, takes this a step further by tolerating the formation of ice within its cells. However, *P. davidi* and many other small semiaquatic organisms are also likely to utilise cryoprotective dehydration, whereby water is lost to ice in the environment, slowly desiccating the animal and removing all freezable water.

Cold hardiness in terrestrial animals has been best studied in the Collembola (springtails) and mites, collectively known as microarthropods. These organisms all utilise a strategy of freeze avoidance—maintenance of liquid body fluids at temperatures well below that at which freezing would occur in most organisms—and consistently die upon freezing. This latter phenomenon has allowed their cold tolerance to be readily measured using thermocouples to detect the latent heat of crystallisation, and therefore freezing events. These freezing temperatures (termed Supercooling Points, SCPs) are examined as population distributions, giving a snapshot of the distribution of cold tolerance in the population. Springtime SCPs as low as –39°C have been recorded in the springtail *Gomphiocephalus hodgsoni* on Ross Island. Low SCPs are made possible by a combination of the animals' small size (most are less than 2 mm long), carbohydrate cryoprotectants (sugar alcohols like glycerol, which act both as an antifreeze and to protect membranes and proteins from conformational changes), and antifreeze proteins, which not only prevent ice nucleation as in fishes but also serve to stabilise the body fluids against spontaneous freezing at very low temperatures.

Compared with animals, the cold hardiness of plants is a less unique feature of the Antarctic biota. Mosses and lichens have a cosmopolitan distribution, and the latter are able to survive temperatures much lower than those ever experienced in the real world. Mosses, lichens, and algae comprise the most southerly recorded living communities, suggesting that exposed rock and liquid water are the main limiting factors for these organisms. Of the vascular plant flora, the freeze-tolerant hairgrass *Deschampsia antarctica* is the more cold hardy, with an LT50 (the temperature at which 50% of the plants die) in the region of –10.4°C in summer and –26.6°C in winter. The pearlwort *Colobanthus quitensis* avoids freezing, but can survive only to c. –9.6°C, and possibly relies on the insulating effects of snow to survive the winter in its maritime Antarctic habitat.

Current cold hardiness research on Antarctic fishes is focussed on understanding the nature of production, distribution, and action of antifreeze proteins within the body, and these proteins are finding biotechnological applications, particularly in the frozen products industry. Research on mite and springtail cold tolerance is leading to a much better understanding of how cold hardiness may be manipulated over short periods of time. At present, nematode cold hardiness research seeks to determine the relative importance of freezing tolerance and cryoprotective dehydration, and to identify specific proteins associated with the survival of intracellular ice formation.

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See also **Adaptation and Evolution; Anhydrobiosis; Fish: Overview; Insects; Parasitic Insects: Mites and Ticks; Seasonality; Springtails; Temperature**

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COLONIZATION

Antarctica has not always been the cold and poor biological environment that we observe today. Presence of coal and fossils of plants suggest that a temperate climate allowed the growth of luxuriant vegetation in the past. However, the subsequent total breakup of the Gondwana, when Australia and the new Antarctic continent parted 65 Ma, was the signal of the strong isolation of this region. For the past 35 million years, this isolation has been reinforced by the Antarctic Circumpolar Current, which acts as a strong barrier, limiting the exchange of marine fauna and flora. During the Quaternary era, the climate was driven by solar (Milankovitch) cycles, and the continental ice sheet fluctuated in cover. Refugia for various organisms probably existed during each glacial maximum, but it is likely that new taxa were introduced into Antarctica during cycles of ice sheet and oceanic front movement.

As a result, the Antarctic fauna and flora exhibit typical features such as low species richness, a strong latitudinal gradient from the cool sub-Antarctic islands to the extremely severe environment on the continent, specific morphological and physiological adaptations, and disharmony of terrestrial food webs, dominated by decomposers with few herbivores and nearly no carnivores. For example, the terrestrial and limnetic Antarctic ecosystems are devoid of native fish, amphibians, reptiles, and herbivorous mammals.

The high rate of endemism in some groups suggests that isolation was a major factor responsible for Antarctic and sub-Antarctic biodiversity: this is clearly demonstrated in some animal taxa such as the Collembola and Coleoptera. By contrast, recent biogeographic studies, based on molecular estimates and accurate paleogeographic reconstructions, indicate that dispersal may have been more important than traditionally assumed. For instance, the dominant pattern in plants is better explained by dispersal than by the vicariant isolation of areas.

A common idea is that Antarctica remains one of the most pristine regions in the world, being exceptionally well protected against the dangers of invasion by alien species because its isolation, the low level of human activity, and its extreme environments should prevent the establishment of new species. However, the biota of most sub-Antarctic islands and some maritime and continental Antarctic ice-free areas include alien taxa. Opportunities for alien invasion have been restricted to the last two centuries, commencing with historical sealing and whaling industries and extending to the research, commercial, and tourist activities of modern times. Introduction of species by human visitors has been facilitated by the low species richness and absence of many functional groups that make islands, and the islandlike exposed land of Antarctica, more susceptible to alien invasion.

Several stages are necessary for successful colonisation: (1) long-distance transport from source populations, including the stochastic aspect of arrival at a suitable colonisation location at a suitable time of year, (2) survival after arrival, and (3) establishment of a long-term reproducing population. Today, despite the strong isolation of sub-Antarctic and

Antarctic territories, the most critical point is not the arrival but the survival and establishment of invaders. Many examples demonstrate the role of humans in the introduction of alien species. Historically, research stations and exploring expeditions have imported a range of mammals and birds for logistic (dogs, ponies), food (pigs, hens), or companionship (cats) purposes, but such activities are no longer permitted on the continent under the terms of the Protocol on Environmental Protection to the Antarctic Treaty. Other taxa have been introduced accidentally (rats, mice, plants). Most alien plants introduced to the sub-Antarctic are European and usually show a large ecological range. Many alien invertebrates and birds are also of European origin, although now cosmopolitan. This is partly because colonization by humans in the Antarctic was largely from Europe. Many of the alien invertebrates recorded as being established on sub-Antarctic islands and found in maritime and continental Antarctic research stations are known to have been imported amongst food and other stores. More generally, many species introduced to the region have been imported with live vegetation, litter, or soil. Human activity in Antarctica has also been identified as a potential source of disease in wildlife by translocating pathogens. For example, avian paramyxoviruses and antibodies to Newcastle Disease have been found in Macquarie Island royal penguins *(Eudyptes chrysolophus)*. Even in the marine environment, a recent survey reported the discovery of the majid spider crab *Hyas araneus* in the Antarctic Peninsula marine waters. This North Atlantic species is the only record of a nonindigenous marine species in Antarctic seas. It may have arrived in Antarctica via ships' sea chests or ballast water.

The increasing number of visitors in Antarctica is also responsible for a greater flux of alien propagules. The number of scientists working on the continent remains fairly stable but the number of ships and tourists increases each year, leading to greater chances of introductions. Tourists are also disproportionately attracted to sites of high diversity, which vary as tourist trends and fashion change.

In addition to the use of ships for transport to Antarctic locations, several national operators and a small number of nongovernmental organisations use air transport. This gives faster and more efficient exchange of personnel and equipment but also allows rapid transfer of propagules, allowing even short-lived life stages to arrive alive.

Climatic amelioration is also likely to enhance the ability of both natural long-distance colonists (especially those with long-surviving propagules) and human-assisted aliens to become established, particularly in the subantarctic. For example, a recent study relating the occurrence of the cosmopolitan necrophagous fly, *Calliphora vicina,* with available meteorological data (1951–2001) at Îles Kerguelen, revealed that establishment of the fly was possible only after the early 1980s and that its continued absence in West Kerguelen is explained by the current climatic conditions there.

The increase in the human activity in Antarctica will likely increase the number and range of taxa arriving in the region, and the ameliorating climate in some areas, such as the Antarctic Peninsula and the sub-Antarctic islands, will most likely increase the probability of survival and establishment of new taxa. In consequences, substantial modifications of Antarctic biodiversity can be expected.

Yves Frenot

See also **Antarctic Ice Sheet: Definitions and Description; Antarctic Peninsula; Biodiversity, Terrestrial; Biogeography; Circumpolar Current, Antarctic; Climate; Diseases, Wildlife; Gondwana; Kerguelen Islands (Îles Kerguelen); Macquarie Island; Protocol on Environmental Protection to the Antarctic Treaty; Tourism**

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COMMONWEALTH TRANS-ANTARCTIC EXPEDITION (1955–1958)

Tentbound due to a blizzard in 1949, Dr. Vivian Fuchs and Dr. Ray Adie conceived the idea of a crossing of the Antarctic continent. Ernest Shackleton had hoped to accomplish it in 1914, but failed. Further discussion in 1950 by Fuchs and James Wordie, who had been Shackleton's chief of scientific staff, led in 1953 to Sir Miles Clifford (governor of the Falkland Islands) asking Fuchs to produce a plan for the crossing. Eighty copies of the original proposal were circulated, which included the following details:

1. The planned route must begin and end in the Falkland Islands Dependencies (later renamed British Antarctic Territory) and the Ross Dependency.
2. The traverse must pass through the South Pole.
3. Assistance could be expected from Commonwealth countries—the United Kingdom, New Zealand, Australia, and South Africa.
4. The expedition must include nationals of all the participating countries.
5. Logistic factors must be sufficiently flexible to ensure a high safety factor.
6. The scientific programme must be sufficient to justify the project.

A high safety factor was desirable to counter the initial resistance to the proposal from certain quarters against the risks of possible failure. The planned route was from the Weddell Sea to the Ross Sea via the South Pole. The plans for the International Geophysical Year (IGY) (1957–1958) had not been made known and neither were those for a US base at the South Pole.

After crossing the Weddell Sea pack ice, the advance party would build Shackleton Base near Vahsel Bay. The advance party would winter over, initiate scientific programming, consolidate the base and travel inland. The next year, the crossing party would arrive, winter over, and establish a small inland base, South Ice. This would function as a winter station and a depot for the crossing party. The Ross Sea exit was known, and if vehicles failed at the head of the Ferrar Glacier, the crossing party could dog sledge or man-haul from the Antarctic Plateau down to the Ross Sea. A single-engine aircraft would cross the continent and then could act as an additional safety factor. A mainly New Zealand party under Sir Edmund Hillary would build a reception station named Scott Base. Air reconnaissance and dog sledging would lay depots up to 700 miles from Scott Base.

All parties would carry out programmes of physiology, geology, geophysics, meteorology, glaciology, exploration, and survey. The Ross Sea party was to survey the western sides of the mountains discovered by Scott and Shackleton. The crossing party would make a gravity and seismic traverse measuring ice thickness.

Being a private expedition necessitated fund-raising and assistance with equipment. Fuchs arranged for heavyweight committees. In London, the twenty-three-member General Committee and eleven-member Committee of Management were both chaired by Marshal of the Royal Air Force Sir John Slessor, and Fuchs was a member. In Wellington, the seven-member Executive Committee had the Hon. C. M. Bowden as chair, A. S. Helm as secretary, and Hillary as a member.

On February 17, 1955, Sir Winston Churchill announced an HMG grant of £100,000, which was followed by a total of £87,000 from New Zealand, South Africa, and Australia. This left a shortfall of some £313,000 to be found from sponsorship from industry, institutions, sale of a book, media, and film rights and contributions from schools.

Staffing was not a problem as some 2000 applications were received. Eight men were appointed for the advance party. Twelve men were selected for the crossing party (including four from the advance party) and four RAF staff for support and for making a transcontinental flight. The crossing party included a New Zealander, an Australian, and a South African. The New Zealand party was staffed with fifteen men and three RNZAF men. In addition, five IGY staff were attached to Scott Base under the administrative responsibility of Hillary. The complement of dogs was twenty-four for Shackleton Base and sixty for Scott Base.

Snow vehicles were improving. The US military and some private expeditions were using ex-wartime petrol Weasel vehicles (the British North Greenland Expedition and the Norwegian-British-Swedish Expedition, 1949–1952). The US military was also using heavy diesel Caterpillar D4–D8 tractors. The TAE transport and engineer officer was empowered to research the field, and with assistance from the Pentagon visited US operations in Greenland. A decision was taken against crevasse-detection equipment (which later proved ineffective in Operation Deepfreeze I) and against heavy diesels for reasons of cost and high risk for an unknown route. Lighter petrol vehicles called SnoCats were found in Greenland but were initially unserviceable; however, inspection showed that with care and modification the risks of SnoCats could be reduced, and they provided a strong competitor for the Weasel.

A decision was made that two vehicles should complete the journey. Engines would be allowed to cold soak—cold starting to be available from –60°F using preheaters and within 40 minutes, or from –40°F without preheating. Achievable speed should be a mean of 20 miles per day in the unknown terrain and short Antarctic summer, and the vehicle would need to haul a heavy load over hard ice, sastrugi, and soft snow. To meet this plan some 340 hours of cold chamber tests and field trials in Norway were carried out and modifications made to all transport (Fuchs and Hillary 1958: 300–320). It was decided for financial and logistical reasons to increase the towed load for SnoCats to 2 × 2 1/2 tons (twice the common amount).

Shackleton Base was supplied with four SnoCats, four Weasels, two Ferguson TE20 tractors, and one Muskeg. Scott Base was supplied with five Ferguson TE20 tractors, and two Weasels were borrowed later from the US Navy. British Petroleum provided research facilities and all fuels and lubricants for ships, aircraft, and snow transport. Lucas provided cold chamber testing and batteries, Smiths the rewiring of the vehicles, BOC the welding gas, and Massey Ferguson the tractors. Many others provided free goods and services.

Operations

Her Majesty the Queen visited the ship, and on November 14, 1955, MV *Theron* (849 tons, 1310 hp), captained by Harald Maro, left London for the Weddell Sea. They met the pack ice on December 22 at 63°50′ S, 30°20′ W. It was not until January 23 that *Theron* sailed back to the edge of the heavy pack ice, having been beset for a month, drifting north and west. Ice damage to the rudder forced Maro to bend it straight by reversing hard into the ice. It appears that for 1955–1956 *Theron* should have entered the pack some 10° to 15° farther to the east before sailing south to reach the narrow open water along the coast. MV *Tottan* (Royal Society) did sail farther east and established Halley Bay station at 75°36′ S, 26°45′ W. *Theron* visited Halley and a TAE Auster flight showed that the area was unsuitable for inland vehicle travel. Hence *Theron* continued and Shackleton Base was finally established on the Filchner Ice Shelf at 77°59′20″ S, 37°09′20″ W, and unloading began on January 30.

On February 1, a gale from the north caused *Theron* to leave her moorings, and five men were left on the shelf ice until the following day. On February 8, the sea was freezing and rafting, and Maro and Fuchs decided that it was time for *Theron* to leave. The eight-man advance party (led by K.V. Blaiklock) was left without an erected hut. Despite criticism from "the inexperienced," the decision to leave proved wise and *Theron* escaped, enabling the TAE to proceed.

The advance party had a harsh experience, sleeping in tents, with a 21′ × 9′ × 8′ SnoCat serving as a kitchen/living room for eight months. On cooking duty for four days in turn, each man slept in the crate and dried out bedding and clothing. A severe blizzard ended on March 26 and it was found that bay ice had broken away, with the serious loss of stores and equipment. They had food for three years but only three gallons of fuel per day. On April 20, when the Sun set for four months, they continued outdoor construction work using Tilley lamps, May was the coldest month (average –35°F) and included a ten-day blizzard. The first radio contact was with a Falkland Islands Dependency Survey (FIDS) base, 12 weeks after *Theron*'s departure. August 2 was the coldest day at –63°F. On October 29, first voice contact was made with BBC London. In November a depot was established 50 miles south, and in December a 360-mile dog sledge journey made Mount Faraway in the Theron mountains (named for the ship). Under extreme conditions, the advance party had completed their tasks, with a base hut virtually constructed, a reconnaissance journey made to the south, and a meteorology programme initiated.

On November 14, 1956, the jointly chartered MV *Magga Dan* (1850 tons, 2020 hp), captained by Hans Christian Petersen, left London, calling at Halley Bay. Unloading at Shackleton Base began on January 14, and the Halley Bay advance party, who were returning to the UK, assisted unloading, and the ship left on January 28.

Otter flights on January 13, 20, 22, and 30 discovered the Slessor Glacier, Recovery Glacier, and the Shackleton Range. A landing was made in the Theron mountains, geological specimens obtained, and a tentative inland route proposed.

Between February 4 and March 26, 1957, some 20 Otter flights established South Ice at 81°56′59″ S, 28°51′40″ W. Three men led by Hal Lister wintered at the station at 4430 feet (where the lowest temperature was recorded at –74°F) and established a programme of meteorology and glaciology.

Meanwhile, the Ross Sea party, comprising 13 New Zealanders, two Englishmen, and three RNZAF men left Wellington in HMR *Endeavour* in December 1956 and arrived on January 4, 1957, to find the planned base site and the Ferrar Glacier route unsuitable. The alternative site chosen was Pram Point, Ross Island. Scott Base was constructed quickly, using an imported construction team, prefabricated section buildings, and a site on rock. On January 18, the Beaver flew the length of the Skelton Glacier. Two dog teams were flown to the Skelton Inlet and reached the Antarctic Plateau in 10 days. A third dog team travelled to the Skelton via White Island and Minna Bluff, and so the route to the plateau was proven quickly for dog teams. In March, Hillary made a 100-mile trip to Cape Crozier to prove his tractors. On October 14, Hillary's party, with three Fergusons and one Weasel, left Scott Base. On December 17, they arrived at Depot 700 following the dog-sledged route, thus proving it for their tractors.

On October 8, South Ice was relieved by air, and one SnoCat and three Weasels (driven by Fuchs, engineer D. L. Pratt, engineer D. E. L. Homard, and seismologist J. G. Pratt) set out to prove a route to South Ice. An air camp was established giving access to the Shackleton range. Two dog sledge units were flown in for survey towards the east, to flag a vehicle route up the ice wall, and for geological work.

Severe crevassing was experienced on the shelf ice, on Recovery Glacier, and south of the glacier toward the Whichaway Nunataks. Manual probing for crevasses was effective but slow. Crevasse crossing required care, and was akin to a tank crossing a minefield, except that one went down instead of up. Factors affecting snow bridge safety were the estimated strength, static and dynamic load imposed, and attrition caused by other vehicles. The greatest risk was not necessarily to the lead vehicle. The traverse of 400 miles lasted 37 days and was completed by the SnoCat and one Weasel on November 19. The pathfinders were flown back to Shackleton Base in two and a half hours. It was a close call when vibration from the two vehicles caused vast 40 × 12 foot holes to blow on either side of the vehicles. The route had proved to be marginally practicable, but by that time there was no alternative.

On November 24, the crossing party finally left Shackleton Base with three SnoCats, one Muskeg, and two Weasels. A dead reckoning traverse with astronomical control was kept. Severe crevassing was met near the Grand Chasm, and one SnoCat was almost lost. It took seven days to travel 22 miles. Poor visibility at Recovery Glacier slowed progress, but the crevasses at the foot of the Nunataks were perhaps the most dangerous. Five hours were required for a second SnoCat recovery, and a Weasel was almost lost.

The 566-mile trip from South Ice to the South Pole was made between December 25 and January 19. The two dog teams surveyed ahead, building cairns every five miles, and met no crevasses. However, several extensive belts of sastrugi up to four feet tall severely stressed the vehicles and sledges.

Meanwhile, the RAF team closed Shackleton Base and flew to South Ice on December 27. Two days later the Otter left for Scott Base, but thick cloud and rime icing forced a return from 87°40′ S. Fortunately, visibility improved to 300 feet, and the Otter pilot followed vehicle tracks into South Ice. To enable refuelling, J. Lassiter (US Ellsworth base) flew two drums from Shackleton Base to South Ice. On January 6, the Otter—the first single-engine aircraft to cross the continent—was successfully flown by John Lewis and Gorodon Haslop in turn from South Ice to Scott Base, 1430 miles in 11 hours. The aircraft could now act as a backup from Scott Base.

The temperature began dropping and the US station at the South Pole was closing down its outside access for the winter. The media had invented the idea of a Fuchs versus Hillary "race." This showed a lack of comprehension about the purpose of TAE. The US base and Hillary were nervous about the weather, and Hillary did not want to winter again at Scott Base. He had extended his tractor journey from Depot 700 to the Pole and arrived with three MF tractors that, although modified, were not suitable for load-hauling in the soft snow of the 10,000-foot-high plateau. The conditions resulted in the tractors being roped together and some of the tents, tools, and food being jettisoned in order to proceed. They arrived with only half a drum of fuel and were totally dependent upon the US South Pole base. The cable from Hillary to Fuchs suggesting that Fuchs stop at the Pole, fly home, and continue the following year caused much world press comment. This was particularly the case when Fuchs declined and explained the crossing party could operate to –60°F and, if necessary, would winter at Scott Base if they should miss *Endeavour*'s return to New Zealand.

Between 24 January and 7 February, Fuchs' party crossed the 520 miles from the South Pole to Depot 700. During his tractor traverse, Hillary had not made a survey of the section, although his party had built cairns in crevassed areas. However, Fuchs' party could not see any of the cairns or the track marks from Hillary's previous crossing. The last 60 miles contained a crevassed belt with some immense crevasses, but fortunately they were well-bridged, and the team progressed safely, with the daily mileage actually improving, as the dogs had been evacuated by the US Navy.

From 10 to 23 February, Fuchs's party crossed from Depot 700 to Plateau Depot, a distance of 445 miles. Hillary joined the crossing party, and his knowledge of the area, the route, and where his tractor marks were to be found proved very valuable, enabling them to make good mileage despite poor visibility. Severe whiteout entailed military-style driving, using hand-placed marker flags.

The 284 miles between Plateau Depot and Scott Base were covered in seven days. Blaiklock and Stephenson were flown out for special duties in Scott Base. The Skelton Glacier produced variable surfaces from hard snow to blue ice and some soft snow patches. Some heavy crevassing was met, but much time was saved since the Ross Sea party had carefully marked a reasonably safe route. Once on the Ross Ice Shelf, the 180 miles to Scott Base were easily travelled, with the best day's run being 75 miles. The 99-day, 2158-mile traverse from Shackleton to Scott Base was completed on March 2, 1958.

The scientific results were recorded in fifteen Trans-Antarctic Expedition reports. A seismic profile of the crossing was obtained by firing charges at some 30-mile intervals, together with more frequent gravity readings as raw gravity. Shackleton Base tides were calculated using a gravimeter. Glaciological studies investigated solid precipitation and drift snow, and snowfall was deduced from combined snow and drift measurement. Geological studies in the Therons and Whichaways found dolerite intrusions in the Beacon System, confirming their presence across the continent from Dronning Maud Land to Victoria Land. The fossil flora confirmed Gondwana affinities. Specimens measured for their palaeomagnetic directions supported the hypothesis of continental drift.

On the Ross Sea side, extensive geological mapping in the previously unexplored regions confirmed details of the Gondwana fossil floras and recognised some of the earliest deposits from the most recent ice age.

In 1957–1958 outstanding exploration survey work was achieved by the three dog sledge parties from Scott Base and the dog sledge parties from Shackleton Base. Physiological research was made into energy balance, acclimatisation to cold in humans, and aspects of the advance party. Engineering studies were conducted into snow friction, engine performances, fuels and lubricants, and metallurgical analysis of materials.

The success of the expedition enriched the knowledge of Antarctica, and, coupled with the outstanding dedication of the leader and the teams, fully justified the industrial, academic, and Commonwealth governments' sponsorship.

David Pratt

See also **Aviation, History of; Dogs and Sledging; Fuchs, Vivian; Hillary, Edmund; Imperial Trans-Antarctic Expedition (1914–1917); International Geophysical Year; Ponies and Mules; Shackleton, Ernest; Wordie, James**

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CONSERVATION

Often described as the last and greatest wilderness on Earth, the Antarctic is the only continent without any indigenous human population. Its remarkable and unique features began to be recognised a century ago but it is only in more recent decades that there has been sufficient data available to identify conservation objectives. The significance of Antarctica in understanding the way in which the Earth functions as a system is now clear and underlines the importance of keeping it as unspoilt as possible.

With less than 0.4% of its land area free of snow and ice, and its distance from the other continental land masses, the potential for colonisation of Antarctica by flora and fauna has been very limited. Although the sea around Antarctica is cold and periodically covered by pack ice, it harbours a much higher diversity than on land and in benthic communities rivals coral reefs for biodiversity. Many of the species involved are unique, both physiologically and evolutionarily. Some groups, such as penguins and seals, have large populations of a few species, and the marine food chain on which all life depends appears significantly simpler than elsewhere in the global oceans.

Although the Antarctic Treaty does not specifically address any particular conservation activities, Article IX requires Contracting Parties to develop recommendations on the "preservation and conservation of living resources in Antarctica." The use of the term "resources" rather than native species, habitats or ecosystems was indicative of the mind-set at the time the treaty was negotiated. The only previous international conservation instrument that concerned Antarctic species was the International Whaling Convention (1947), which was concerned entirely with the management of what was then a major commercial resource.

In general terms there are two conceptual approaches to conservation. One is general defining principles to provide protection from damaging effects of present or future activities. The second is more specific and deals with the management of specific activities to limit or mitigate damage. Underlying both is the concept that the Antarctic needs to be protected and managed for the benefit of all humankind. These approaches were defined soon after the treaty was concluded, and the general approach to Antarctic conservation can be considered as largely precautionary, with the parties attempting to regulate activities before damage occurs rather than after impacts have been noted.

Soon after the first meeting of the treaty parties (I ATCM), the scientific community recognised the immediate need for formal conservation objectives. At III ATCM in 1964, a proposal from the Scientific Committee on Antarctic Research (SCAR) was accepted and the Agreed Measures for the Conservation of Antarctic Flora and Fauna set out the first detailed conservation principles for Antarctica. The Agreed Measures prohibited citizens of a treaty party from killing, capturing, or molesting without a permit any mammal or bird native to the Antarctic. In addition they allowed for the designation of Specially Protected Species, but failed to define the criteria for designation. Participating governments were required to take appropriate measures to minimise harmful interference with native mammals or birds. Harmful interference was defined as allowing dogs to run free, flying aircraft or driving vehicles so as unnecessarily to disturb bird and seal concentrations, using explosives or firearms close to such concentrations, or disturbing the animals during the breeding season by persistent attentions from persons on foot. Habitat protection for areas of outstanding scientific interest was established by means of Specially Protected Areas (SPAs).

In 1966, the first fifteen SPAs were declared, and the Ross Seal and fur seals were scheduled as Specially Protected Species. At this stage it had been assumed that the Agreed Measures could be applied only to land areas and ice shelves south of 60° S, based on the way they were linked to the geographical coverage outlined in Article VI of the treaty and on international high seas rights. However, many parties saw this as too restrictive and by 1975 the Consultative Parties had reinterpreted the measures to allow the designation of limited marine SPAs.

Collecting specimens or entering SPAs required a permit issued by an "appropriate authority" under the Agreed Measures. There was no specific indication that permits issued by one government must be recognised by every other one, but that is the practice that was adopted. Parties soon recognised that there were limitations to the SPA concept. It appeared it could not be applied to nonbiological sites, there were no specific management plans or individual rules on entry, and since the sites had to be exceptional there was no way to apply the concept of protection to sites being used for scientific research and monitoring. To address this last point the proposal for Sites of Special Scientific Interest (SSSI) was introduced at VIII ATCM to allow research areas to be protected. These sites were required to have management plans and maps and had to be designated for a finite period since it was implicit that once the research or monitoring was completed the designation should be withdrawn. This designation could also be applied to nonbiological sites and was quickly used to protect Arrival Heights, Ross Island, as a site for atmospheric research. Although it has always been possible to apply both designations to protect sites of geological interest, this has only been infrequently used. The most recent analysis of Antarctic Specially Protected Areas, in 2005, showed that there were sixty-two sites protecting 1780 km^2 of sea and 960 km^2 of land. This represents less than 0.008% of the total Antarctic Treaty area. There is also a very unequal distribution both geographically and biologically of the sites.

After this initial codification of procedures the treaty parties began to develop a broad range of legal instruments for conservation and environmental management. The next major instrument was also motivated by the precautionary principle. Exploratory voyages to assess the potential for commercial harvesting of crabeater seals had alarmed SCAR and many treaty parties, who decided to develop a new instrument that would allow more rigorous control and oversight over all Antarctic seals. In 1972, the Convention on the Conservation of Antarctic Seals established several new principles for Antarctica. It explicitly recognized that marine resources could be subject to sustainable harvesting within an agreed international management framework. The convention not only defines total allowable catch (no more than 10% of the population) but also establishes that measures limiting species, sex, age or size, methods of sealing, and areas or periods closed to sealing ("seal reserves") can be specified to protect the stock. Inspection of activities as well as mandatory catch returns to SCAR were also established. SCAR is specifically required to provide scientific assessments on the effects of sealing on stocks to allow treaty parties to actively manage the commercial activity. Since the convention was adopted there has been no attempt to start commercial sealing.

More ambitious was the next conservation instrument. Increasing levels of fishing in the Southern Ocean by the Soviet Union, Poland, and several other countries during the late 1960s and 1970s began to alarm marine scientists. The secrecy inherent in all Soviet and East European activities at the time of the Cold War meant that there were inadequate data available to document the extent of the catches, but trawler fleets on station in the Southern Ocean year-round were certainly suggestive of large catches. As it was already suspected that fish grow only very slowly in the cold water there was a real threat of serious depletion. In addition there appeared to be a growing commercial interest in krill. The key role of krill in the Southern Ocean food web meant that overfishing would have damaging effects on whales, seals, and birds. In particular, since the International Whaling Commission had recognised that catastrophic overfishing of all species of large whales could only be addressed by a complete moratorium on whaling to allow stocks to recover, it was felt that any large scale krill fishery might seriously impair the recovery of whale populations. In addition IWC had earlier created whale reserves to limit harvesting of particular species. To attempt to manage all marine living resources on a sustainable basis, the treaty parties signed the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) in 1980 and it entered into force in 1982. It had three especially novel features. First, its boundary was not politically determined at 60° S as per the Antarctic Treaty but at the biological boundary of the Antarctic Polar Front. Second, the management objective was to protect the integrity of the marine ecosystem rather than manage each species stock independently. This was a revolutionary approach to fisheries management and was the most developed move towards marine sustainability anywhere in the world. And third, decisions were taken by consensus, which was a lesson learnt from the IWC where majority voting had introduced bitter disagreements between countries.

Adequate management of a major industry such as fishing requires good catch data, a clear understanding of the life cycles of the target species and their relationships with the surrounding food web and a monitoring programme to ensure that the catch quotas really are set to have no lasting effect on ecosystem structure and function. Its management regime for sustainability is thus implicitly a major force for marine conservation in the Southern Ocean. CCAMLR has an annual meeting of those countries that have ratified it during which the national representatives are informed by previous discussions in a scientific committee. There is an international secretariat in Hobart, Tasmania, to manage the data, an inspection system for the fishery vessels, a catch certification scheme to allow all catches to be traceable when sold, and long-term international monitoring of the effects of fishing on key elements of the marine ecosystem at sites around the Antarctic. In addition there are a variety of mitigation measures to avoid unwanted bycatch of both birds and marine species and areas can be closed to fishing, effectively providing temporary marine reserves. This system should provide all the elements required for sustainable management, but unregulated pirate fishing of some stocks (especially Patagonian toothfish) is destroying the legitimate licensed fishery and undermining all conservation efforts.

Mineral resources are not mentioned anywhere in the Antarctic Treaty as they were seen as too contentious an issue for discussion when the original text was being negotiated. In 1970, New Zealand noted the lack of any form of regulation dealing with Antarctic minerals and raised concerns that an uncontrolled scramble, if any significant deposits were found, would have very damaging effects on the environment. There was, and is, no scientific evidence to support contentions that there are economically valuable deposits either on land or under the sea, but public myths developed suggesting otherwise and the parties began to discuss the problem. By 1977, they had agreed that some form of regime for management was required. Formal negotiations began in 1982 and by 1988 agreement had been reached on the Convention on the Regulation of Antarctic Mineral Resource Activities (CRAMRA). Contrary to public (and indeed political) opinion in some countries, CRAMRA was never intended to be a regime that facilitated and promoted Antarctic mining. Instead it constitutes a mechanism for assessing the effects of proposed mineral resource activities on the environment, and determines whether they are acceptable and what will be required in terms of mitigation and remediation. The protection of the Antarctic environment is the key thread that runs through CRAMRA and since agreement to proceed is by consensus there are substantial political checks involved on precipitate or unacceptable activities. To come into force CRAMRA required ratification by all those countries that were claimant states. CRAMRA was not seen in a positive light by many environmental nongovernmental organizations, who set about establishing public opposition to ratification. Greenpeace was especially active in this. For political reasons Australia, then New Zealand, and finally France all decided not to ratify and so CRAMRA failed.

Yet all was not lost from a conservation viewpoint. A groundswell of international public concern was being orchestrated at this point by two nongovernmental organizations, Greenpeace and the Antarctic and Southern Ocean Coalition (ASOC). The NGOs saw that there was an opportunity to press for increased protection for the Antarctic environment and the treaty parties reacted swiftly to this. In the space of two years, through a series of special meetings, the parties drafted the Protocol for the Protection of the Antarctic Environment. This was an enormous step forward in that it revised and codified all the previous environmental legislation, introduced new concepts on how to achieve agreed objectives and stipulated a ban on all mining and mineral extraction for 50 years. Many of the important elements were taken from the failed CRAMRA legislation that had already been negotiated. The protocol may be reviewed after 50 years, if requested by any of the Consultative Parties.

The core concepts for the protocol were different to all previous attempts to organise conservation and environmental management. First, it covered all human activities in the treaty area, except those already covered by CCAMLR and IWC legislation. Second, it recognised the complexity and diversity of national legislatures and the need to be able to keep the environmental management processes up-to-date without requiring further primary legislation. To achieve this the protocol has a descriptive core of general principles that were assumed to have a considerable degree of permanency and form the primary legislation, followed by annexes devoted to management processes that may be enacted by executive order or a similar instrument. Whilst this was the route followed by many countries others failed to understand the practical importance of separating the two elements and turned parts or all of the annexes into primary legislation. The effect of this has been that these countries are now unwilling to agree to changes in the annexes that would both improve the use of the annexes and reflect changes in environmental best practice since they were negotiated.

The protocol establishes several new concepts and reiterates important existing ones within its general text. In some areas it is perhaps the most stringent environmental legislation on earth. In other areas, it is completely lacking. Antarctica is described as a "natural reserve devoted to peace and science." Most significantly, all activities must planned and conducted so as to limit their adverse impacts. The protocol, and indeed the text of the Antarctic Treaty itself, allows for official inspections of facilities, ships and abandoned worksites by other treaty parties. The Environmental Impact Assessment of all activities is mandatory and codified. The conservation of flora and fauna is further strengthened by the link to "associated and dependent ecosystems." Measures to prevent marine pollution were strengthened, in particular in light of the 1989 *Bahia Paraiso* pollution incident, and build upon the Special Area status accorded to the seas south of 60° S under MARPOL 73/78. Waste management was more rigorously defined. The protocol also simplified the protected areas system, distinguishing between areas set aside for conservation, research and monitoring (Antarctic Specially Protected Areas) and areas set aside for management through codes of conduct (Antarctic Specially Managed Areas). Considerable effort is being expended at present on linking the criteria for endangerment devised by IUCN and used throughout the world (except for the Antarctic) to the designation and management of the concept of Specially Protected Species in Annex II of the protocol. This requires a significantly different view of conservation (as a dynamic tool rather than a recipe for preservation) to that used previously by the parties in that species would be removed from the SPS list once they were no longer endangered.

There is also now a new liability annex to attempt to deal with environmental damage.

An important part of the protocol was the establishment of the advisory Committee for Environmental Protection at which it was intended to have scientifically informed discussions on all aspects of conservation and environmental management. It was envisaged as providing the Antarctic Treaty with a nonpolitical "environmental science committee" in the same way that the CCAMLR Commission is advised by its Scientific Committee. Whilst there has been considerable progress in this new forum with many individual conservation issues it remains more political than scientific on many subjects, delegations often lack adequately experienced scientific advisors and the major interactions are limited to a small number of countries.

In the early 1980s, Greenpeace and other NGOs mounted a campaign for the declaration of Antarctica as a World Park managed by the United Nations rather than by the Antarctic Treaty parties. Their grounds for this was the premise that the continent was the inheritance of all humankind, that such a designation and management regime was the only way to be certain of adequate conservation and rejection of commercial exploitation, and that laws made by the UN would be universally accepted to conserve the Antarctic for future generations. To attract publicity for its position Greenpeace established World Park Base on Ross Island for a 5-year period, aiming to show that scientific research and environmental responsibility could coexist in a way that they claimed was not implemented by many treaty parties. A number of countries outside the treaty that regularly raised questions of Antarctic governance and conservation at the United Nations showed considerable sympathy for this approach. Most treaty parties apparently felt that the long-term protection of the continent was better served by the efforts of those most committed to the Antarctic. In implementing CCAMLR and the Protocol for Environmental Protection, the treaty parties met virtually all the conservation and environmental management demands raised by the NGOs, including admitting them as Experts to the annual Treaty Consultative Meeting.

There have been other conservation activities outside the Antarctic Treaty. The World Conservation Union (IUCN) signed a World Conservation Strategy in 1980 with the intention of developing various regional implementations. One such was the Strategy for Antarctic Conservation, resulting from a joint initiative with SCAR over a period of 5 years, and published in 1991. Although all the Consultative Parties in 1991 were also members of IUCN, they were at that point completely occupied by the protocol and its implementation and paid little attention to the IUCN document. The twenty-first century now needs a new version of this framework, linking the elements of the protocol to conservation activities at a global scale.

The high levels of mortality in albatross and petrels linked to longline fisheries encouraged international efforts to develop a transboundary agreement for their protection and conservation anywhere in the world. The Agreement for the Conservation of Albatrosses and Petrels, a part of the Convention on the Conservation of Migratory Species of Wild Animals, entered into force in February 2004 and is now actively developing new initiatives to protect these birds and reverse the catastrophic declines in many populations.

Introduced species are a potential problem for Antarctic conservation, but there is as yet only limited evidence of the establishment of new species in either the marine or terrestrial ecosystems. A long-established patch of introduced grass on Deception Island was obliterated in the eruption in 1969 and has not reestablished. Nonnative invertebrates have been reported from Signy Island, introduced through contaminated soil used for trials of introduced plants. Flies have been reported breeding at Casey and Rothera stations, although such introductions are synanthropogenic. It seems likely that other invertebrate species will be found near other stations, for example on King George Island, where there have been numerous introductions of soil for potted plants and greenhouses. In the marine realm a recent report of male and female North Atlantic spider crabs in a site west of the Antarctic Peninsula has stimulated interest in examining possible pathways for marine introductions so that suitable monitoring and controls can be developed. Both ballast water and hull fouling are suspected as possible routes for introductions, but there is as yet only limited data. Monitoring for propagules in cargo and on clothing have shown that humans may carry a considerable number of new species into the Antarctic in the form of seeds and spores, many of which have been shown to be viable. A warming climate in the Antarctic Peninsula region makes it increasingly likely that future conditions will allow establishment of species from elsewhere and the increasing numbers of scientists, logisticians, and tourists to this region are regarded by some as providing previously unrealised opportunities for transport of seeds, spores, plant fragments, and insects.

There has been increasing concern about the possibility of introduced diseases causing major mortality in Antarctic birds and seals. As data on foraging for these species has accumulated it is clear that many species actively visit areas outside the treaty area and potentially come into contact with other species carrying a wide range of diseases. There has also been some survey work which has identified antibodies to specific diseases in Antarctic penguins. Although there have been some reports of local disease outbreaks, as yet there is no evidence that the risk of introduction of diseases likely to cause mass mortality has substantially increased. It is clear, however, that much basic information on disease in the Antarctic fauna remains to be gathered.

Several initiatives have produced guidelines or codes of conduct for sensitive sites. These provide a degree of protection for specific sites without the formality of the international declaration of a specially protected area. The most significant were the ones developed by the USA and New Zealand for the McMurdo Dry Valleys, which have since been incorporated in the Antarctic Specially Managed Area plan. These guidelines provide a sound basis for good practice in environmental management and conservation anywhere on the continent.

Environmental guidelines were developed by IAATO for all passengers going ashore and for many years have been a required basis for tourist management. The ATCM adopted these guidelines as Recommendation XVIII-1. Increasing numbers of tourists visiting a limited number of sites has induced the ATCM to begin drafting site guidelines for the most heavily visited sites. Whilst there is as yet no agreement on how to estimate carrying capacity for these sites nor, in many cases, is there clear evidence yet of significant cumulative damage, this new initiative is intended to be precautionary in nature.

The Convention on Biodiversity does not apply to the Antarctic so that its framework for managing genetic resources cannot be applied there. Treaty parties have already recognised that bioprospecting is a developing field and have noted that there are now over 300 patents arising from biochemical and genomic studies on Antarctic organisms. The relationship between these activities and conservation remains to be explored in the future.

Despite the opportunities to ensure that modern conservation in the rest of the world is reflected in Antarctic legislation the Consultative Parties have shown themselves lagging significantly behind activities elsewhere. The lack of connectivity is all the more surprising as these same countries, but through different government departments, have agreed to conservation and monitoring initiatives for their national territories which they seem unwilling to contemplate in the Antarctic. The activities at the CEP have the potential to avoid this in the future if parties can find ways to improve connectivity and consultation within countries between their departments responsible for representation at the ATCM, at CCAMLR and at general conservation and environmental treaties.

Sub-Antarctic Conservation Initiatives

The sub-Antarctic islands that ring the Antarctic continent are all nationally governed. Almost all of these islands have suffered from human impacts over the past 150 years leaving them with some potentially difficult conservation and management problems. Introduced plants and animals constitute major impacts on the native communities of many of the islands and governments are struggling at present to address these. This is a problem for many islands worldwide and has attracted the interest of the United Nations Environment Programme as a major concern for preserving global biodiversity. All of the sub-Antarctic islands, except the French ones of Îles Crozet and Îles Kerguelen, now have published environmental management plans.

The most serious problems have resulted from the introduction of rats with their impact on burrowing petrels, grazing animals and their effect on the native vegetation, and plants that out-compete native species and replace native communities. Some islands have also had problems with cats that eat birds, with mice, and with introduced invertebrates that damage native plants or consume native invertebrates.

The most successful control measures so far have been the elimination of cats from Marion Island and the reduction in rabbit numbers on Macquarie Island. Trials to eliminate rats using baiting techniques have been successful on Île St. Paul and are underway on South Georgia and Kerguelen. There have been culls of the cattle on Île Amsterdam. On Kerguelen, trout have been introduced into some lakes and rivers on Isle Grande whilst on Marion Island the mouse population is rapidly expanding and causing impacts on the invertebrate populations.

On South Georgia the two reindeer herds have caused considerable damage to native plant communities and allowed the establishment of swards dominated by the introduced species Annual Meadow Grass *(Poa annua)*. On the Barff Peninsula the overgrazing has been extensive in several areas causing landslips. Fenced plots have demonstrated that over 25 years there is unlikely to be any reestablishment of the original plant communities on the Barff if the reindeer are removed. The Busen herd on the other hand have not yet destroyed the integrity of the native communities.

Erosion and wind-assisted loss of soil on many of the islands in the Kerguelen archipelago is a matter of considerable concern. The very extensive overgrazing, mainly by rabbits but assisted in many areas by reindeer, mouflon, and sheep, has reduced the native plant stands in many areas to a domination by *Acaena magellanica,* which is itself grazed. Grazing by the cattle on Île Amsterdam has largely destroyed the native vegetation and allowed many aliens to become established.

On Marion Island the eighteen known introduced plant species have spread considerably and now form a significant component of many communities. However, South Africa's rigorous quarantine regulations and severe limits on visits have kept the neighboring Prince Edward Island almost completely free of all introduced species, with only three species reported, two of which may have been introduced by natural vectors. A similar rigorous approach by Australia to Heard Island has also kept that island almost free of introduced species.

The special features of these sub-Antarctic islands have prompted some governments to apply for World Heritage listing for some islands. Heard Island and Macquarie Island are both now been accepted as World Heritage Sites by UNESCO.

Exploration of Antarctica has left a range of buildings and previously inhabited sites that are a substantive contribution to Antarctic history. The conservation of these sites has been undertaken in a variety of ways. The Antarctic Treaty has a conservation category for Historic Sites and Monument and now over seventy of those have been agreed and listed by the Consultative Parties. They range from rock cairns and plaques, marking previously inhabited sites, to graves and huts from earlier expeditions.

The more substantive remains of Heroic Age exploration, in particular the huts built by the expeditions lead by Carsten Borchgrevink, Robert Falcon Scott, Ernest Shackleton, and Douglas Mawson, are all now managed by specialised conservators with continuing efforts to preserve both the fabric and the contents. The New Zealand Antarctic Heritage Trust, with support from Antarctica New Zealand, has the responsibility for the Ross Island huts of Scott and Shackleton whilst Australian Antarctic Division is engaged in conservation work at Commonwealth Bay on Mawson's hut. On the Antarctic Peninsula, Argentina has worked with Sweden to preserve the remains of Otto Nordenskjold's hut on Snow Hill Island and manages the huts, magnetic observatory and graveyard left by the Scottish National Expedition on Laurie Island, South Orkney Islands. The UK Antarctic Heritage Trust, working with British Antarctic Survey, is undertaking the conservation and management of early FIDS huts at four sites—Port Lockroy, Argentine Islands, Stonington Island, and Horseshoe Island. Port Lockroy has been extensively restored to its original condition in the 1950s and now constitutes a living museum, staffed each summer to manage visits from over 10,000 tourists. The ATCM has adopted a conservation strategy for Antarctica's most significant whaling remains, on Deception Island. The USA has undertaken conservation work on the remains of the building that housed the Ronne Expedition on Stonington Island.

On the sub-Antarctic islands the relevant national authorities have made considerable efforts to conserve key sites. At South Georgia the whaling station at Grytviken has been made safe and laid out as an open air museum, whilst on Îles Kerguelen there is a continuing programme of restoration of the original buildings at Pointe Jeanne d'Arc whaling station. Many of the islands have sealing sites which are also being recorded whilst efforts are being made on Crozet to preserve a very early whaling and sealing site in Baie Americaine.

DAVID W. H. WALTON

See also **Agreement for the Conservation of Albatross and Petrels; Amsterdam Island (Île Amsterdam); Antarctic and Southern Ocean Coalition; Antarctic Peninsula; Antarctic Treaty System; Archaeology, Historic; Australasian Antarctic Expedition (1911–1914); Birds: Specially Protected Species; British Antarctic *(Nimrod)* Expedition (1907–1909); British Antarctic *(Southern Cross)* expedition (1898–1900); British Antarctic *(Terra Nova)* expedition (1910–1913); British National Antarctic *(Discovery)* Expedition (1901–1904); Convention on the Conservation of Antarctic Marine Living Resources; Convention on the Conservation of Antarctic Seals; Convention on the Regulation of Antarctic Mineral Resource Activities; Crozet Islands (Îles Crozet); Deception Island; Diseases, Wildlife; Dry Valleys; Fisheries and Management; Food Web, Marine; Greenpeace; Heard Island and McDonald Islands; International Whaling Commission (IWC); International Convention for the Prevention of Pollution from Ships (MARPOL); Kerguelen Islands (Îles Kerguelen); King George Island; Macquarie Island; Prince Edward Islands; Protected Areas within the Antarctic Treaty Area; Protocol on Environmental Protection to the Antarctic Treaty; Ronne Antarctic Research Expedition (1947–1948); Ross Island; Scientific Committee on Antarctic Research (SCAR); South Georgia; South Orkney Islands; St. Paul Island (Île St. Paul); Tourism; World Conservation Union (IUCN); Zooplankton and Krill**

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CONSERVATION OF ANTARCTIC FAUNA AND FLORA: AGREED MEASURES

History

The Agreed Measures to promote nature conservation in Antarctica were adopted by Resolutions III–VIII of the Third Antarctic Treaty Consultative Meeting (ATCM) held in Brussels in June 1964. The Antarctic Treaty Consultative Parties (ATCPs) involved were Argentina, Australia, Belgium, Chile, France, Japan, New Zealand, Norway, South Africa, the USSR, the UK, and the US.

The first text of a "Suggested Form of Measures to promote Conservation of Nature in the Antarctic" was prepared in March 1959 by Dr. Martin W. Holdgate for the Working Group on Biology of the Scientific Committee on Antarctic Research (SCAR). A revised text was approved by the SCAR Executive in May 1961. It emphasised the scientific importance of the Antarctic flora and fauna and set out detailed proposals for a possible legal instrument.

Dr. Brian B. Roberts played a leading part in negotiating Recommendations I–VIII, adopted by the first ATCM, held in 1961. This ATCM urged governments to develop internationally agreed conservation measures, and issued interim "General Rules of Conduct for Preservation and Conservation of Living Resources in Antarctica" based on the SCAR proposals. The governments then negotiated the Agreed Measures, adopted in 1964. Pending confirmation by all ATCPs they were implemented on a voluntary basis. They became binding in 1982.

Content

The Agreed Measures applied to all land, freshwaters, and ice shelves within the Antarctic Treaty area, which was recognised as a Special Conservation Area. The detailed articles:

- Prohibited the killing, wounding, capture or molestation of all native mammals and birds except in accordance with a permit;
- Allowed governments to issue permits for the taking of specimens for research, museums, or zoos and to provide indispensable food for people or dogs;
- Provided for the designation of Specially Protected Areas and Specially Protected Species;
- Prohibited the introduction of nonindigenous plants and animals (except carefully controlled nonavian domestic species, under permit);
- Demanded strict control of potentially damaging activities such as allowing dogs to run free, flying helicopters or driving vehicles near bird and seal colonies, using explosives, or persistently disturbing wildlife in the breeding season.

Development

Following the adoption of the Agreed Measures, in November 1966, SCAR prepared a first list of fifteen proposed Specially Protected Areas (SPAs) and recommended Specially Protected status for the Ross Seal and all species of fur seals. These were adopted at the 4th ATCM in Santiago, Chile, also in November 1966. In 1972, provision was made for designating Marine Protected Areas and Sites of Special Scientific Interest (SSSI) managed for scientific research. By 1991, twenty-four SPAs, thirty-seven SSSIs, and one Specially Managed Area (SMA) had been designated (some of the original SPAs being transferred to the SSSI list).

Although a landmark statement of policy, the Agreed Measures did not have full Antarctic Treaty status or deal with such matters as waste disposal, pollution prevention, or the assessment of the environmental impact of new development, which were the subject of separate ATCM decisions. In 1990, the ATCPs agreed to negotiate a new Protocol on Environmental Protection to the Treaty itself, and this entered into force in 1998. It superseded the Agreed Measures which were, however, restated (with some adjustments) as Annex II to the protocol. All the SPAs and SSSIs were relisted in a new category, Antarctic Specially Protected Areas (ASPAs), and management plans for these areas have been adopted at various subsequent ATCMs.

MARTIN HOLDGATE

See also **Antarctic Treaty System; Birds: Specially Protected Species; Convention on the Conservation of Antarctic Marine Living Resources; Protected Areas within the Antarctic Treaty Area; Scientific Committee on Antarctic Research (SCAR)**

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CONTINENTAL SHELVES AND SLOPES

Antarctica is one of two island continents (the other being Australia) and hence is completely surrounded by its continental shelf and slope. This marine border comprises an astounding 1.5×10^4 km in circumference and some 4.36×10^6 km^2 in area extent, as measured along the shelf break and for the continental shelf respectively. Along this continental periphery are to be found some of the world's greatest relief and bathymetric complexity. Our knowledge of the Antarctic margin is a study in contrast. Vast regions remain unsurveyed and yet with the increased use of mulitbeam swath mapping in the last 10 years portions of the Antarctic margin are better known in detail than many seafloors around the world.

A general definition of a continental shelf holds that the shelf represents a submerged continuation of the continental physiography beyond the coastline, to some distance (on average 80 km) over which the prevailing seaward slope of the ocean floor is gentle (1:1000) and in continuity with the landscape inland of the coast. The coastal boundary in Antarctic is somewhat variable depending upon whether one is focusing upon the sea surface contact with an ice shelf, its submerged grounding line, bedrock, or a tidewater glacier margin (GEBCO 2003).

As a continent with a long glacial history, one that extends back at least 32 million years, Antarctica has a continental shelf that exhibits evidence of deep glacial erosion and sediment progradation (Johnson et al. 1982). The depth of the shelf is also influenced by the presence of the continental ice sheet via isostatic depression of the crust. The continental shelf break delineates the boundary between the shallow continental shelf and the continental slope, the latter of which represents a steep, ever-deepening incline that can be up to 200 km wide. The continental slope merges with a broad apron of the continental rise at depths of ~2000–3000 m. Together the shelf, slope, and rise constitute the continental margin.

Tectonics

The deep, underlying tectonic context for most of the Antarctic periphery is one of a passive, rifted margin. In such settings the shelf and slope reflect an origin related to continental rifting and subsequent continental drift. The timing of separation between Antarctica and its Southern Hemisphere neighbors ranges from 115 Ma for Africa, 90 Ma for India, 75 Ma for New Zealand (Campbell Plateau), 33 Ma for Australia, to 30 Ma for South America. Such progressive isolation over the last 100 million years is generally believed to have contributed to the development of Antarctica's ice sheet, although it is becoming increasingly clear that punctuated shifts in the earth's atmospheric composition during the Cenozoic may have also played a significant role (Zachos et al. 2001).

The pattern of passive tectonism for the Antarctic margin is broken along a 450 km stretch bordering the South Shetland Islands, near the Antarctic Peninsula. Here a small segment of oceanic crust of the Scotia/Drake plates is actively subducting beneath the edge of the South Shetland microcrustal plate, producing a 5000 m South Shetland ocean trench and associated volcanism. The related South Shetland platform) is narrower (50 km) than the rest of the continental shelves surrounding Antarctica.

The overall deep physiography of the Ross Sea, and indeed much of West Antarctica, is due to protracted crustal subsidence which is focused within continental rifting that borders the Trans Antarctic Mountains. This process of crustal extension is overprinted by glacial erosion, which reduces relief and rift volcanism and uplift that constructs relief.

General Physiography

In many ways the continental shelf and slope surrounding Antarctica escape both the physiographic and political definitions applicable to the rest of the world's continental margins. First, the depth of the Antarctic shelf is far greater than the global average, 500 m versus 100 m. Second, the progressive and gentle seaward slope of most of the world's shelves is not typical for Antarctica. Instead, deep troughs extend well below 1000 m (up to 2000 m) along both the inner shelf, as near coast-parallel features, and out across the shelf itself, as transverse troughs, to the shelf break. Consequently relief is far greater on the Antarctic continental shelf than in any other shelf region of mid to low latitude. However, the shelves of Greenland, Norway, and the NE Canadian Arctic are quite similar to Antarctica because they share a glacial history (Johnson et al. 1982).

The deeper crustal structure of the Antarctic margin is inherited from the rifting phase and, as with most mid to high latitude passive margins, has largely been buried beneath a seaward thickening wedge of terrigenous sediment. In the case of Antarctica the sediment wedge comprises a thick succession of glacial and glacial marine deposits (Anderson 1999) that date back to the earliest Oligocene (Barrett 1999). However due to deep glacial incision across the inner portions of the shelf the underlying structure of the margins is revealed in the pattern of bathymetric troughs which highlight contrasts in crustal composition, such as from crystalline basement to sedimentary rock. These so-called coast-parallel troughs are the deepest features in the world's shelves and some extend to just over 2000 m. They owe their origin to selective linear erosion beneath ice streams and ice sheets over many periods of past glaciation.

In comparison, somewhat more shallow troughs cut across the shelf toward the shelf break and these transverse features are interpreted as sites of enhanced erosion due to localization of convergent flow or ice streaming during Neogene glacial expansion. In both such features mesoscale seabed features such as megascale glacial lineations, bundles, and drumlins, mark the streamlining effect of past glacial flow upon glacial sediments and even bedrock (Anderson 1999; Canals et al. 2000).

Much of the continental shelf of Antarctica (nearly 35%) actually lies beneath large floating ice shelves (some 1.5 million km^2). The implications of this are that much of the bottom remains inaccessible to direct observation. However, bathymetric maps of the sub-ice-shelf seafloor have been produced via geophysical surveys across the ice shelves (Vaughan et al. 1994). A significant portion of the continental shelf also lies beneath impenetrable sea ice, mainly portions of eastern Wilkes Land and in the Amundsen Sea sector. These regions lack any sounding data whatsoever. The future use of robotic survey technology may improve our knowledge of those areas.

Regional Variability in Physiography

The geographic division of West Antarctica and East Antarctica applies equally to the character of the associated continental shelves. West Antarctica includes both the elongate Antarctic Peninsula and the pronounced embayments of the Weddell Sea and Ross Sea.

The Weddell Sea Region

The Weddell Sea is the oldest of the continental margins having formed from the separation of Africa some 115 Ma. The margin is largely covered by the floating extent of the Ronne-Filchner Ice Shelf and the persistent pack ice of the Weddell Sea. The shelf is broad and extends with an unusually wide continental slope and rise to a width of 300 to 500 km. It is delineated by a series of broad troughs and banks including the prominent Crary Trough (1200 m deep, 500 km long, and 100 km wide), Berkner Bank, General Belgrano Bank, and Ronne Basin. The Crary Trough is an extension of the subglacial Thiel Trough, which runs an additional 200 km beneath the West Antarctic ice sheet beyond the grounding line (Drewry 1983).

The Antarctic Peninsula Region

The Antarctic Peninsula presents a striking juxtaposition of two continental margins on opposite sides of an elevated (up to 2.5 km) but narrow (only 50–200 km wide) landmass. The western or Pacific side is broad (on average 200 km wide) and deeply incised into several transverse troughs, the deepest of which extend into near shore areas (Rebesco et al. 1998). The largest of these is the Marguerite Trough, which extends 400 km, from the George VI Ice Shelf between Adelaide Island, Alexander Island, and Palmer Land. The Palmer Deep is one of the deepest inner shelf troughs, dropping to over 1400 m in depth. The Palmer Deep is found offshore Anvers Island and the Graham Land coast, near the US Palmer Station (Domack et al. 2005). The Palmer Deep is like other such inner shelf basins along the western Antarctic Peninsula as it is fringed by a channeled morphology, strongly suggestive of erosion via subglacial meltwater processes (Lowe and Anderson 2002). The channeled regions of the inner shelf transition seaward into a more streamlined glacially sculpted seafloor that is more typical of the rest of the Antarctic continental shelf. Beyond the shelf the continental slope is characterized by extensive sediment mounds and channels that are linked genetically to shelfwide glaciation (Amblas et al. 2005).

The Eastern or Weddell Sea side of the peninsula is less well known and is near inaccessible in most years due to the heavy Weddell Sea pack ice. Yet the shelf here comprises one of the widest features of the Antarctic continental margin extending on average 250 km. It appears to be less deeply incised, as inner shelf troughs extend to 800 to 1000 m, some 400 m less than basins on the western side of the Antarctic

Peninsula. Transverse troughs also appear to be broader with less well defined margins (Evans et al. 2005). But, as with much of the Antarctic margin, a great deal remains to be discovered and mapped in the NW Weddell Sea.

Amundsen Sea Region and the Ross Sea

A significant portion of the continental shelf runs from the Amundsen Sea to the Ross Sea, offshore Marie Byrd Land and Victoria Land. This portion carries from 100° W to 170° E and represents the most varied portion of the entire Antarctic continental shelf. The Marie Byrd Land coast is punctuated by three major embayments: the Ronne Entrance/Eltanin Bay, Pine Island Bay, and Sulzberger Bay. In places the shelf is as wide as 440 km, and is not extensively surveyed. Between these embayments continental promontories extend seaward, causing the shelf to narrow to less than 90 km.

The Ross Sea opens into a very broad shelf that extends beneath the Ross Ice Shelf (Davey 2004). In fact most of the shelf is covered by the ice shelf, with the open water portion extending some 180 to 620 km north, beyond the calving line. In the far western Ross Sea the full width of the shelf runs parallel to the Victoria Land coast and includes some 1200 km, 650 km of which extend beneath the ice shelf to the grounding line. The shelf is marked by a highly lineated set of transverse troughs and banks.

East Antarctic Margin

The East Antarctic continental shelf runs from 170° E to 25° W, roughly from Cape Adare (North Victoria Land) in the east to the Riiser-Larsen Ice Shelf to the west, a total distance of 7800 km parallel to the margin. Much of the margin remains unexplored yet there are some areas of intense study, such as within Prydz Bay. Most work along the margin has been conducted by the Australian Antarctic Division, the Russian Antarctic Program and the Japanese Antarctic Program, with some contributions from the US, Italian, and to a lesser extent the French Antarctic Programs. Within the total length of the continental shelf there are three distinct physiographic regions: Wilkes Land, Prydz Bay, and the composite of Queen Maud Land and Enderby Land continental shelves.

Wilkes Land comprises the eastern sector and on average is 170 km wide with minor deviation from this mean. The shelf is marked by a progression of *en echelon* inner shelf troughs (coast parallel) that project toward the northwest and are interrupted by transverse troughs. The deepest region of the Antarctic continental shelf is found just west of Casey Station where the inner shelf trough reaches just over 2000 m depth (at 66°08′ S and 109°08′ E).

Prydz Bay constitutes a large extension of the Lambert Graben, a rift basin that serves to drain the Lambert Glacier and its floating terminus, the Amery Ice Shelf. The physiography of Prydz Bay is basically like that of a large transverse trough and it extends at least 320 km, making it much wider than the rest of the East Antarctic continental shelf and therefore distinct (O'Brien 1994).

To the west the continental shelf of Enderby Land and Queen Maud Land is uniformly narrow, at about 90 km wide. It is dissected in places by very narrow and somewhat sinuous transverse troughs unique for this margin. A good example is the Nielsen basin, which winds its way across the Mac.Robertson shelf just east of Mawson Station. The Queen Maud Land shelf is distinct as well in that along its western end, toward the Weddell Sea, fringing ice shelves such as the Riiser-Larsen and Fimbul ice shelves cover nearly the entire extent of the shelf where they float out over the upper continental slope or shelf break.

Sediments

Seafloor sediments on the Antarctic continental shelf are varied and range from relict glacial tills, reworked (palimpsest) deposits of varied texture, and recent muds to diatom oozes. Their distribution is controlled by water depth, ice cover, and regional bathymetry. The most recent glacial expansion across the continental shelf took place during periods of lowered sea level coincident with Northern Hemisphere ice sheet growth during the late Pleistocene (about 20,000 years ago). Subsequent melting and recession of the great northern hemisphere ice sheets allowed global sea levels to rise, thus initiating instability along the expanded Antarctic ice sheet periphery that led to recession toward the modern coastline. The seafloor reflects this episode of glacial expansion and retreat in the fact that poorly sorted subglacial sediments (tills) cover most of the continental shelf. In addition these poorly sorted glacial sediments were sculpted by glacial flow into a variety of streamlined bedforms ranging from classic drumlins to increasingly elongate ridges and grooves referred to as megascale glacial lineations and bundles. Morainal banks also mark the glacial termini (Anderson 1999). Where glacial sediments remain exposed at the seafloor they comprise a relict surface which can be observed in many places to be overgrown by epifaunal (encrusting) organisms.

Most commonly the glacial sediments are disturbed by the plowing action of icebergs, a process that may have been more pervasive during deglaciation, when icebergs were probably more numerous and larger than today. Modern iceberg turbation is limited to depths generally less than 400 m and produces a variety of large to intermediate scours, pock marks, and impressions that migrate across the banks and outer continental shelf. In some regions iceberg scour has completely obliterated the relict glacial morphology of the seafloor and resulting palimpsest sediments have been sorted by a combination of iceberg ploughing and resuspension.

In some regions where strong currents interact with the seafloor, such as the outer shelf and shallow banks, bedload transport of sorted sand and bioclastic (skeletal) carbonate takes place forming veneers above the glacial sediment. Some mesoscale bedforms (dunes or sandwaves) result in many of these sandy regions attesting to the efficiency of current action.

The deep troughs of the continental shelf serve as important depocenters for modern (Holocene) mud and ooze. In fact some of the highest accumulation rates in the world's oceans are to be found along portions of the East Antarctic continental shelf, where up to 200 m of Holocene mud and siliceous ooze are to be found. These sediments form distinct deposystems referred to as drifts and drapes that form under the influence of variable bottom currents or blanket the underlying seafloor evenly in the absence of currents, respectively. Their distribution is generally limited to water depths greater than 500 m, within enclosed basins that are separated from the continental slope by broad sills. The accumulation of these fine grained sediments is often so rapid that the occurrence of ice-rafted debris (poorly particles released by icebergs) is often diluted or not evident with the mud. This is a somewhat odd association given the abundance of debris-laden icebergs observed across the continental shelf today.

Bathymetric Database

The General Bathymetric Chart of the Oceans (GEBCO, www.bodc.ac.uk) maintains a compilation of single-channel survey data collected over the years in collaboration with a number of international organizations including the Scientific Committee on Antarctic Research (SCAR). Charts and data are now available digitally as part of a global atlas of the ocean floor. The data are easily accessible although are somewhat lacking in the detail provided by more recent multibeam surveys of the region. At present five nations routinely collect multibeam data across the Antarctic continental margin. The respective nations and platforms are the US Antarctic program (RVIB *N. B. Palmer*), the British Antarctic Survey (RV *James Clark Ross*), the German Polar Program (RV *Polarstern*), the Spanish Antarctic Program (RV *Hesperides*), and the Italian Antarctic Program (RV *Explora*). These data are archived with the various national programs. An Internet-based data set is archived on GeoMapApp (www.geomapapp.org) which includes nearly 75% of all the US multibeam data acquired across the margin in the last 10 years. The most completely mapped region is the northern Antarctic Peninsula and several national programs are collaborating to provide integrated seafloor maps of the region. It is likely that with the onset of the International Polar Year in 2007–2008 several integrated efforts will soon be published or be made available electronically.

Traditional bathymetric charts are published by the US Defense Mapping Agency, the British Admiralty, the Australian Antarctic Division, the Canadian Hydrographic Office, and the German Hydrographic Office. Many of these databases are included in Chilean and Argentinean charts of Antarctic offshore waters. Coarse resolution bathymetric data can also be obtained from electronic versions of satellite data derived from gravity and ocean surface elevations (Smith and Sandwell 1997).

Legal Continental Shelf and Law of the Sea

The United Nations Convention on the Law of the Sea (UNCLOS) treats the continental shelves of the world as economic zones for each country along the respective coastal border. In addition, exclusive economic zones (EEZ) extend to depths beyond the typical continental shelf but to no more than 200 nm. For a number of reasons it is unclear how this agreement applies to the continental shelf of Antarctica. While living marine resources are protected in the Southern Ocean (for instance through the Convention on the Conservation of Antarctic Marine Living Resources agreement) and exploration and/or extraction of mineral deposits is not allowed (the Madrid Environmental Protection Protocol), seabed resources are not clearly protected in any existing agreement. While the establishment of a Special Conservation area with the Antarctic region could (under the Madrid Protocol) protect a portion of marine seafloor from economic activity, the broader rights of any nation under international law related to the high seas are indeed preserved in Article VI of the Antarctic

Treaty. Yet in Article IV, paragraph 2, treaty nations are explicitly prevented from extending or in any way modifying the territorial claims made prior to the signing of the treaty in 1959. Since the EEZ associated with continental shelves went into effect with UNCLOS in 1980 it does not appear that an EEZ can be applied to the Antarctic continental shelf (even if the portion of the shelf in question is adjacent to territorial land claims). This condition will hold as long as the Antarctic Treaty remains in effect.

EUGENE W. DOMACK

See also **Antarctic Treaty System; Geological Evolution and Structure of Antarctica; Glacial Geology; Ice Shelves; Icebergs; Sediments and Paleoceanography of the Southern Ocean; Southern Ocean: Bathymetry**

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CONVENTION ON INTERNATIONAL TRADE IN ENDANGERED SPECIES OF WILD FAUNA AND FLORA (CITES)

History

The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) was adopted at Washington DC on 3 March 1973 and entered into force on 1 July 1975. By July 2004 there were 166 state parties. All the state parties to the Antarctic Treaty are also parties to CITES.

The convention originated from concerns expressed at the 8th Session of the General Assembly of the International Union for Conservation of Nature and Natural Resources (IUCN) held in Nairobi in 1963 over "the export, transit and import of rare or threatened wildlife species or their skins or trophies." Between 1964 and 1970 successive texts of a draft treaty prepared by the IUCN Commission on Law were circulated to about ninety governments and international organizations. The driving force was Dr. Wolfgang Burhenne, then chair of the commission and legal adviser to the Bundestag (German parliament).

The IUCN text was criticised (notably by the United States) for its unduly European style, and the negotiations in Washington, D.C., in 1973 were based on an alternative prepared in consultation with the United Nations Environment Programme. UNEP also accepted responsibility for providing the Secretariat to the Convention, although between 1973 and 1984 it used IUCN as its agent. Conferences of Parties to CITES are now held every 4 years in different cities around the world.

Content

CITES has a relatively narrow focus. It seeks to safeguard species that are threatened with extinction by *international* trade. It operates by placing such species in one of three appendices. Appendix I lists those most severely endangered and permits trade only in exceptional circumstances. Appendix II lists species whose international trade is controlled in order to avoid utilization incompatible with their survival. Appendix III lists species that are protected, in particular countries that have asked other CITES parties to assist them by controlling trade. Where trade is permitted, CITES requires detailed export and import certificates, records being supplied to the CITES Secretariat.

Development

Since its adoption, the number of states party to CITES has more than doubled, making it the most widely supported of all international conservation treaties. Revisions of listings in the appendices are considered by Conferences of Parties, where expert advice is provided by IUCN (especially its Species Survival Commission), WWF (the World Wide Fund for Nature), and the UNEP World Conservation Monitoring Centre in Cambridge, UK.

Antarctic Relevance

CITES overlaps with other international legal instruments, including the Antarctic Treaty and its Protocol on Environmental Protection, the International Convention on the Regulation of Whaling, and (potentially) the Convention on the Conservation of Antarctic Seals. All species of great whale are listed in Appendix I, as are fur and elephant seals. These listings have been questioned because there is virtually no commercial trade in these species today, and hence no threat from it—but the listings have been retained because any proposal to resume commercial exploitation would restore what was obviously a severe threat in the past. If whaling were to resume, the products could not be traded internationally unless the species were delisted or transferred to CITES Appendix II, and this would certainly be hotly contested. Similarly, should Antarctic sealing commence, attempts might be made to block international trade in the products by proposing listings under CITES. The convention cannot therefore be wholly disregarded as a potential factor in Antarctic politics.

MARTIN HOLDGATE

See also **Antarctic Fur Seal; Antarctic Treaty System; Convention on the Conservation of Antarctic Seals (CCAS); Protocol on Environmental Protection to the Antarctic Treaty; Southern Elephant Seal; United Nations Environment Programme (UNEP); Whales: Overview; World Conservation Union (IUCN)**

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CONVENTION ON THE CONSERVATION OF ANTARCTIC MARINE LIVING RESOURCES (CCAMLR)

The Southern Ocean surrounds the Antarctic Continent. It is seen as being confined south of the Antarctic Convergence (or Polar Front) at about 50° S where cold Antarctic waters meet warmer northern waters. The Convergence constitutes a relatively effective biogeographical barrier for marine species to the south, thereby characterizing a single, large Antarctic marine ecosystem around the Continent.

Humans commenced hunting and fishing in the Southern Ocean during the eighteenth century. These activities often had extremely negative impacts on the animal populations being exploited and they comprised cycles of intensive fishing followed by depletion of target species then a switch to other stocks. For example, many large whales were virtually exterminated in the early to mid-twentieth century in a harvesting progression that moved from large to small species. A number of Southern Ocean fish species have also been reduced to very low levels.

By the mid-1970s, Antarctic krill *(Euphausia superba)* was seen as a major food item for many Southern Ocean whales, seals, birds and fish, as well as a fishery resource of almost limitless potential. This led to concern that krill overharvesting could negatively affect the entire Southern Ocean marine ecosystem leading to recently protected whale populations failing to recover with other species dependent on krill as a food source also being detrimentally affected.

The 1977 Antarctic Treaty Consultative Meeting therefore initiated negotiations, under Treaty Article IX, which culminated in the 1982 Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR, pronounced "kammelar"). Together with the 1964 Agreed Measures for the Conservation of Antarctic Fauna and Flora, the 1972 Convention on the Conservation of Antarctic Seals and the 1991 Protocol on Environmental Protection to the Antarctic Treaty (Madrid Protocol), CCAMLR is an important element of the Antarctic Treaty System.

All CCAMLR parties are eligible to become members of an associated commission that oversees the convention's implementation. Initially, fifteen states signed the convention in September 1980. Eight of these (Australia, Chile, Japan, New Zealand, South Africa, the Soviet Union [after the dissolution of the USSR in 1991, responsibilities were assumed by Russia], United Kingdom, and United States) subsequently ratified the convention, which lead to its entry into force on April 7, 1982. All these CCAMLR parties became commission members and were later joined by a further sixteen states (Argentina, Belgium, Brazil, France, German Democratic Republic [commission membership ceased on 2 October 1990 following unification with the Federal Republic of Germany], Federal Republic of Germany, India, Italy, Namibia, Norway, Poland, Republic of Korea, Spain, Sweden, Ukraine, Uruguay) and the European Community. An additional seven countries (Bulgaria, Canada, Finland, Greece, Netherlands, Peru, Vanuatu) are parties to the convention, but are not members of the commission.

Excepting seals south of 60° S and whales, the CCAMLR applies to all marine living resources between the Antarctica and the Antarctic Convergence. In carrying out its tasks, the commission works closely with institutions implementing the Convention on the Conservation of Antarctic Seals and the International Convention for the Regulation of Whaling as well as the Committee for Environmental Protection under the Madrid Protocol.

As many animals (e.g., birds) cross the convention's northern boundary, the commission also cooperates with other international organisations and national institutions responsible for living resource management and conservation in adjacent areas or in the oceans generally. Most notably, these include the Food and Agriculture Organisation (FAO) of the United Nations (UN) and the 2002 Agreement on the Conservation of Albatrosses and Petrels. CCAMLR also shares a close affiliation with the Scientific Committee on Antarctic Research (SCAR).

The commission's main objective is to conserve marine life in the area for which it is responsible. This does not exclude harvesting carried out in a sustainable (i.e., "rational") manner following the various principles set out in CCAMLR Article II. Nonetheless, this objective is difficult to achieve. It not only requires the collection of large quantities of information, it also requires development of appropriate management, scientific and analytical techniques.

The commission uses advice from various subsidiary bodies to guide its management activities. These include the Standing Committee on Implementation and Compliance (SCIC) and the Scientific Committee (SC-CAMLR). The latter bases its recommendations on scientific assessments carried out by its Working Groups on Ecosystem Monitoring and Management (WG-EMM) and Fish Stock Assessment (WG-FSA).

As economic interest in CCAMLR-regulated resources increases, there is a growing temptation to harvest these resources in defiance of the organisation's regulatory measures. Since 1996, this has lead to a dramatic increase in illegal, unreported and unregulated (IUU) fishing in the CCAMLR Area, particularly for toothfish *(Dissostichus spp.)*. The Southern Ocean's vastness and inclement weather make it extremely difficult for member states to enforce or police commission measures to combat such fishing. The commission has therefore developed a comprehensive suite of measures, including an innovative scheme to monitor toothfish trade, landings, and imports.

Like many other regional agreements, CCAMLR does not impose or police its own regulations. Rather it agrees on measures that its members are legally obligated to implement and enforce. The recent entry of non-CCAMLR members into the lucrative toothfish fishery has compounded the commission's efforts to combat IUU fishing and promote enforcement of its management measures to the extent that such fishing now constitutes a major threat to CCAMLR's effectiveness.

The commission strives to implement a holistic or ecosystem approach to the management of the resources for which it is responsible. This approach distinguishes CCAMLR from many other international fisheries agreements as it addresses both direct and indirect effects of harvesting on ecological linkages between species. To improve understanding of relevant ecological linkages, the CCAMLR Ecosystem Monitoring Program (CEMP) was set up in 1985 to monitor and understand "natural" as opposed to "human-induced" variability in the Antarctic marine ecosystem. On the strength of such initiatives, the

CCAMLR commission leads the way in developing ecosystem-based approaches to marine living resource management.

CCAMLR's ecosystem approach also requires exercising a level of precaution in developing management measures. This strives to minimize risks associated with unsustainable practices in the face of uncertainty arising from incomplete knowledge of either the fishery, or species, concerned. Again, the CCAMLR commission leads the way internationally in developing precautionary ecosystem management approaches. In particular, its efforts to develop operational definition of key parameters and precautionary reference points preempted many later instruments agreed under the 1982 UN Convention on the Law of the Sea. This has allowed the commission to account for uncertainty in many of its conservation measures and to react in a proactive rather than reactive manner to prevailing, or changing, circumstances.

DENZIL G. M. MILLER

See also **Antarctic Divergence; Antarctic Treaty System; Conservation; Conservation of Antarctic Fauna and Flora: Agreed Measures; Convention on the Conservation of Antarctic Seals; Fish: Overview; Fisheries and Management; Food Web, Marine; International Whaling Commission (IWC); Marr, James; Polar Front; Protocol on Environmental Protection to the Antarctic Treaty; Scientific Committee on Antarctic Research (SCAR); Seabird Conservation; Southern Ocean; Toothfish; United Nations Convention on the Law of the Sea (UNCLOS); Whaling, History of; Zooplankton and Krill**

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CONVENTION ON THE CONSERVATION OF ANTARCTIC SEALS (CCAS)

History

The Convention on the Conservation of Antarctic Seals (CCAS) was adopted in 1972 and entered into force in 1978.

Unregulated sealing led to the near-extinction of fur seals, *Arctocephalus tropicalis gazella,* at South Georgia and in the South Shetland and South Orkney Islands between 1775 and 1820. In the twentieth century the resurgent fur seal population at South Georgia was effectively protected and the exploitation of southern elephant seals, *Mirounga leonina,* was strictly regulated. The adoption of the Agreed Measures for the Conservation of Antarctic Fauna and Flora by the Third Antarctic Treaty Consultative Meeting (ATCM) in June 1964 brought special protection to fur seals and Ross seals, *Ommatophoca rossi,* on land and shelf ice south of 60° S, but did not affect the rights of treaty parties on the high seas.

In August–September 1964, MV *Polarhav* made an exploratory voyage to the Antarctic and killed 322 seals in pack ice around the South Orkney Islands. Of these, 218 were crabeaters, *Lobodon carcinophagus,* recognised as the world's most abundant seal, with estimates of total Antarctic populations ranging from 13 million to 35 million animals. Although the theoretical annual sustainable yield from this population was calculated in the millions, there was concern that an unregulated industry might develop and overexploit the resource.

In response, the Scientific Committee on Antarctic Research (SCAR) drew up "Guide Lines for the Voluntary Regulation of Antarctic Pelagic Sealing" in 1966 (extended in 1968). The Convention on the Conservation of Antarctic Seals (CCAS), as a free-standing international legal measure, was negotiated in London in 1972. The driving force behind CCAS was Dr. Brian B. Roberts of the Scott Polar Research Institute and UK Foreign and Commonwealth Office, who believed strongly that international regulations should be drawn up in advance of commercial development and the establishment of vested interests. The initial signatories of CCAS were Argentina, Australia, Belgium, Chile, Japan, New Zealand, Norway, South Africa, United Kingdom, USA, and the USSR. Subsequently, Brazil, Canada, Germany, Italy, and Poland acceded. New Zealand has not ratified CCAS but has attended meetings as an observer, as have Peru and Sweden.

Content

CCAS applies to all seas south of 60° S. The preamble emphasises that Antarctic seal stocks are a resource of potential value which should be used in a rational way, with harvests at or below the optimal sustainable yield, and sealing operations should be conducted in ways that will not disturb natural ecosystems. The initial annual catch quotas were for 175,000 crabeater, 12,000 leopard, and 5000 Weddell seals. Ross, fur, and southern elephant seals are accorded total protection, and Weddell seals are protected in their breeding season. Zones (identical to those used by the whaling industry) are closed to sealing in rotation, and sanctuaries are defined around the South Orkney Islands, in the southwestern Ross Sea and in Edisto Inlet. Records of all seals taken are to be kept, and data exchanged between contracting parties. SCAR is charged with special responsibilities for research and advice on catch limits. The CCAS was to be reviewed by conferences held at 5-year intervals.

Development

Although CCAS entered into force in 1978 and was reviewed in 1988, no commercial sealing has taken place in the Antarctic since its adoption. International opinion has meanwhile hardened against commercial sealing, while the Antarctic region has become increasingly valued as an international protected area. It seems unlikely, therefore, that CCAS will become an operational regulatory instrument, but it remains available for use if the need arises.

MARTIN HOLDGATE

See also **Antarctic Fur Seal; Antarctic Treaty System; Conservation of Antarctic Fauna and Flora: Agreed Measures; Crabeater Seal; Leopard Seal; Ross Seal; Scientific Committee on Antarctic Research (SCAR); South Georgia; South Orkney Islands; South Shetland Islands; Southern Elephant Seal; Weddell Seal**

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CONVENTION ON THE REGULATION OF ANTARCTIC MINERAL RESOURCE ACTIVITIES (CRAMRA)

Following the signature of the Antarctic Treaty in Washington in December 1959, it was predicted that the treaty would collapse as soon as any mineral resource was found worth exploiting. By 1982, no such mineral had been found; so why did the Antarctic Treaty Consultative Parties embark on what many saw as a "mission impossible"? Elsewhere in the world mineral resource activity is regulated on the basis of acknowledged ownership of the resource itself or the land it is in by a person or a state. No such basis existed in Antarctica.

Three arguments led the Consultative Parties, some reluctantly, to take up this challenge. The first was that mineral activity in Antarctica carried environmental risks of a much higher order than elsewhere in the world. (What might happen if an iceberg collided with an offshore oil rig?) The second was that in the absence of a governing agreement, it was not possible definitively to deny that prospecting for minerals in the Antarctic might take place (a high proportion of the world's mineral resources have been found by people who were not looking for them). The third was that if a mineral resource were found in Antarctica before an equitable international regulatory regime had been established, negotiating such a regime afterwards would be virtually impossible.

The negotiations began in June 1982 in Wellington, New Zealand, between Argentina, Australia, Belgium, Chile, France, Federal Republic of Germany (as it then was), Japan, New Zealand, Norway, Poland, the Union of Soviet Socialist Republics (as it then was), the United Kingdom, and the United States. By the end of the negotiations in June 1988 Brazil, China, German Democratic Republic, India, Italy, and Uruguay were also participating as Consultative Parties. The convention consists of 67 articles, covering prospecting for, exploration of, and exploitation of any mineral resources in the Antarctic Treaty area.

In addition to environmental impact assessment procedures required at every stage leading to exploitation there was an innovatory *sufficiency of information test* that had to be passed before any affirmative decision could be made—the information provided in an environmental impact assessment might the best available, but was it sufficient? At each of numerous decision points leading to exploitation it was required that a judgement be made as to whether *enough* was known to make an *informed judgement* about the probable environmental impact were a positive decision to be made—if not, no go.

Had CRAMRA entered into force the development of this sufficiency of information test would have added greatly to the armoury of environmental protective measures available in international law. But within a year after its adoption the convention was dead following the decisions of Australia and France not to ratify it, and within a further two years the convention had been replaced by an outright ban on all mineral resource activity (except scientific research) in Article 7 of the Protocol on Environmental Protection to the Antarctic Treaty (Madrid 1991).

John Heap

See also **Antarctic: Definitions and Boundaries; Antarctic Treaty System; Geopolitics of the Antarctic; Protocol on Environmental Protection to the Antarctic Treaty; United Nations**

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COOK, JAMES

The three voyages of James Cook (1728–1779) are better remembered for the warm seas of the tropical Pacific than for the long and arduous investigations of the icy latitudes. But his systematic demolition of the theories that a southern continent existed in habitable latitudes was a hard-won discovery that brought reality to geographical speculation and left the outlines of the Pacific looking much as they do today.

A southern continent had been appearing on maps and charts since the days of the ancients, who argued that a large land mass had to exist in the Southern Hemisphere in order to balance the continents in the north. The precise size and location of this mythical continent was something of a mystery, but it was generally placed somewhere in the South Pacific Ocean, which, because of the strong westerly currents and winds prevailing in high latitudes, had remained uncharted by European ships entering the ocean from the east, even though they had been doing so since 1520.

In the 1760s, an English East India Company official, Alexander Dalrymple, began forcefully lobbying the British government for a full-scale search for the continent, which, he said, would be found in the latitude of 40° S. The potential commercial rewards were enormous, he argued, for it was larger than Asia with a population of 50 million people and was, moreover, rich in mineral resources. In 1767, Samuel Wallis, aboard *Dolphin,* thought he might have seen this continent's outline on the horizon south of Tahiti. A year later James Cook was ordered to follow up Wallis's report and establish a British claim to the continent once the observations of the transit of Venus at Tahiti—the primary purpose of the *Endeavour* voyage (1768–1771)—were completed.

Cook entered the Pacific in the usual way around the bottom of South America and sailed northwest across the Pacific to Tahiti. From there he made due south for seven weeks but found no trace of the continent and turned back, returning to Britain via New Zealand and Australia. But he was conscious that his had been a tentative foray and one that still left unanswered questions. He began to develop a plan for a systematic search that would take advantage of the prevailing winds and currents rather than fight against them. Instead of entering the Pacific from Cape Horn he would approach from the opposite direction, sailing south from Cape Town into high latitudes and circling the globe in an easterly direction, wintering in New Zealand. This plan became his second and greatest voyage of exploration, on *Resolution* and *Adventure* (1772–1775). As on his first voyage, he took scientists to study the natural history of the continent—not Joseph Banks this time, but the father-and-son team of naturalists, Johann Reinhold and Georg Forster.

Resolution and *Adventure* headed south from Cape Town at the end of November 1772. The expedition searched initially for Cape Circumcision, reported by the French navigator Bouvet in 1739 and believed by him to be part of the southern continent. Bouvet's position was inaccurate, his cape was in fact a small island, and Cook failed to find it anyway, so the ships pushed on south. The cold was intense. Cook issued thick, warm clothing made from a material called "Fearnought," supplementing it with extra rations of spirits as often as he thought necessary. By the middle of December visibility was poor in the frequent snow and sleet storms, and ice was a constant threat to his small vessels, neither of which had reinforced hulls. The icebergs were also a source of fresh water, and as Cook shared the contemporary belief that salt water could not freeze, he thought the ice could only have come from fresh water; he speculated correctly—but for the wrong reason—that land therefore did exist farther to the south, although it would prove to be uninhabitable even if it could be reached.

On January 17, 1773, *Resolution* and *Adventure* became, as far as is known, the first ships to cross the Antarctic Circle. At this point they were unknowingly little more than 70 miles from the continent of Antarctica, but pack ice stretched before them and Cook prudently turned north and east. The ships became separated in thick fog and after again trying to cross the Antarctic Circle but being stopped by ice, Cook headed east towards a rendezvous in New Zealand, where *Resolution* and *Adventure* met again in April 1773.

Here Cook departed from his original plan and spent the southern winter in a leisurely sweep through the central Pacific islands before continuing the search for the southern continent. The ships became separated once more and were not to meet again, as Tobias Furneaux, the commander of *Adventure,* headed for home via Cape Horn and Cape Town, reaching as far as 61° S. The *Resolution,* however, pushed farther south, reaching the exact antipodes of Britain on December 7, 1773, and crossing the Antarctic Circle on December 20. Conditions once more were appalling: the sails froze solid, as did the sheaves in the blocks, "so that it required our utmost effort to get a Top-sail down and up; the cold so intense as hardly to be endured." Cook turned north, causing great excitement and relief among the crew. Their hopes were dashed a few days later when he turned south again, having achieved his aim of intersecting his old course across the Pacific in 1769, so establishing that the continent could not exist in that particular triangle of the ocean. On January 30, 1774, they reached a new farthest south, 71°10′ S, and were prevented from going farther by ice.

Although he had proved conclusively that a southern continent did not exist in the Pacific and the original intention had been to now return to Britain, Cook decided to spend one more summer extending the search into the South Atlantic. The decision was not popular among his exhausted officers, scientists, and crew, but the next spring the ship obediently turned south once more, discovering the isolated island of South Georgia, which impressed no one, before finally setting a course for Cape Town and home. "A final end [has] been put to the searching after a Southern Continent," wrote Cook with some feeling, "which has at times ingrossed the attention of some of the Maritime Powers for near two Centuries past and the Geographers of all ages."

Nigel Rigby

See also **Bouvet de Lozier, Jean-Baptiste; Bouvetøya; South Georgia**

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COPEPODS

The subclass Copepoda is a group of small aquatic crustaceans arguably forming the most abundant multicelled animal group on the planet, exceeding even insects and nematodes in number. The name copepod is derived from the Greek words "kope" meaning "oar" and "podos" meaning "foot," referring to their paddlelike swimming legs. They are diverse, with more than 10,000 species described, inhabiting aquatic habitats worldwide, from the deepest ocean trenches to Himalayan lakes. They comprise both free living and highly specialised symbiotic and parasitic forms. Free-living copepods are planktonic (i.e., drifting in the water), in marine, intertidal, and freshwater habitats and also occupy sediments, seaweeds, and damp terrestrial and subterranean habitats. Planktonic copepods, the most numerous and ecologically important group, are typically small, often 0.5–5 mm, and are segmented. Copepods are highly adapted to aquatic life, with their fossils dating back at least to the mid-Cretaceous period, more than 100 Ma.

In the Southern Ocean, copepods are the most numerous and conspicuous components of the zooplankton (i.e., animal plankton). Here, their diversity is highest in the warmer water found at depth, where many species characteristic of lower latitudes are found. The colder surface layers are characterised by low copepod diversity, and a high proportion of large, endemic Antarctic species.

Three orders of copepods are prevalent in Antarctic waters. The first, Calanoida, includes characteristic marine species such as *Calanoides acutus, Calanus propinquus,* and *Rhincalanus gigas,* and the freshwater *Boeckella poppei*. The second comprises a group of highly numerous small species including *Oithona similis,* which can exceed 10,000 individuals per m^3 of seawater. The third group, Harpacticoida, includes *Drescheriella glacialis,* one of the few species adapted to exploiting the rich feeding within sea ice.

Both in Antarctica and worldwide, the free-living copepods form important intermediaries in the food web. By feeding on phytoplankton (i.e., planktonic algae) and protozoans, they connect the base of the food web to higher trophic levels. Major copepod predators in Antarctica include petrels and fish, as well as a wide range of larger zooplankton species. Therefore, alongside Antarctic krill, they are important in the marine ecosystem, both in terms of supporting commercially fished species and in terms of biogeochemistry, in the ocean carbon cycle. In addition to herbivorous copepods, there are also many detritus feeders, omnivores, and carnivores.

The life cycles of the important planktonic copepods of Antarctica involve egg laying, often in the spring at the time of the phytoplankton outburst or "bloom." This timing provides a food resource for the various instars to grow rapidly in near-surface layers in spring and summer, moulting through six nauplius stages and six copepodite stages. The last copepodite stage is the adult, which completes the life cycle. Given the intense seasonality of polar marine habitats, winter food can be scarce for herbivorous zooplankton. Thus copepods may overwinter in diapause at depth (similar to hibernation), or by feeding at low rates and more carnivorously, or by feeding on algae associated with sea ice.

Angus Atkinson

See also **Algae; Carbon Cycle; Fish: Overview; Growth; Marine Trophic Level Interactions; Protozoa; Sea Ice: Microbial Communities and Primary Production; South Georgia; Southern Ocean: Biogeochemistry; Zooplankton and Krill**

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CORMORANTS

Cormorants are web-footed, mainly fish-eating, aquatic birds, occurring in both marine and fresh waters. They belong to the avian order Pelecaniformes, which they share with five other families: the pelicans, gannets and boobies, darters (anhingas), frigate birds, and tropic birds. A total of thirty-five species is usually recognized, all within a single genus and family (*Phalacrocorax,* Phalacrocoracidae), although some taxonomic treatments allow for more genera and a greater number of species. Cormorants are widespread globally, occurring in most seas and on inland waters on nearly all continents. They are largely absent, however, from tropical marine waters.

Only one species is a breeding resident within Antarctic and sub-Antarctic waters, the imperial cormorant *Phalacrocorax atriceps,* for which a number of taxa has been described. A modern genetic study has yet to be published on this taxonomically confusing group, so the conservative treatment followed here should not be regarded as the last word on the subject. Indeed, it is quite likely that the various taxa will be awarded full species status (as they are already in some accounts). If this happens, then many of them will automatically become single-island or island group endemics, and will then have to be considered for inclusion within the "red data list" of globally threatened species.

Overview of Biology

The imperial cormorant (often referred to as the imperial shag, and also as the blue-eyed cormorant or shag) is a large, primarily blue-black (dorsally) and white (ventrally) seabird with a thin, hooked bill, striking blue orbital ring, bright orange caruncles (bare raised skin) at the base of the bill and, in prebreeding or display plumage, a distinct crest. The closed wing usually (but not in all taxa) shows a white bar. Legs and feet are a dark pink in adults. Juvenile birds are less brightly marked, without obvious eye ring, caruncles or crest, and their dorsal plumage is more brown than black. Nonbreeding adults are also less conspicuous, usually lacking a crest. The species has a body length of 65–75 cm and a body mass of 2000–3500 g. The sexes are alike in appearance, although like all cormorants, males are somewhat larger and heavier than females. There are slight differences in size and appearance between the various taxa recognized within the species group.

Imperial cormorants have a large range, occurring in southern South America, the Antarctic Peninsula, and at most maritime Antarctic and sub-Antarctic islands in the southern Atlantic, Indian, and Pacific oceans. The species is absent from the larger part of the Antarctic Continent. It also does not occur on the more northerly cool-temperate islands of the

Southern Ocean, such as the Tristan da Cunha Group in the south Atlantic or on the various island groups south of New Zealand (the latter of which each have their own distinct species of island-endemic cormorants). Other than in South America, where some birds can be found on freshwater lakes, the imperial cormorant is a strictly marine species. The total population has been estimated as between 300,000 and 1,300,000 individuals, the large range reflecting the lack of adequate surveys at many breeding sites. Because of its large numbers and wide range, it is not considered to be globally threatened, and has thus been classified as "Least Concern" by BirdLife International.

Imperial cormorants breed in colonies during the austral summer, usually close to the water's edge on raised rocks or on cliffs tops and offshore stacks, building nests of seaweed and terrestrial vegetation that becomes cemented by guano. Prior to breeding, adult birds assume a "prenuptial" plumage, with the crests being particularly noticeable. Birds breed monogamously, with incubation and chick-rearing duties shared between the sexes. However, the male first occupies the nest site and builds the nest. For seabirds, fidelity to mate is low (as it seems to be in several cormorant species studied in detail, so it may well be a general trait of the whole family), and birds often take new partners between seasons. They lay from two to four white unmarked eggs, which they incubate by drawing them onto their webbed feet. Staggered hatching leads to young of differing sizes, which compete for food regurgitated by their parents; as a consequence only the older (and larger) chicks may survive to fledging. Breeding may commence at three years of age, but the average age of commencement is closer to five years. Breeding success fluctuates from year to year, probably related to changes in the inshore food supplies of the species.

The species is a resident one, not undertaking any migrations of note. It is an inshore forager during daylight hours, diving from the sea surface and foraging on the sea bottom, primarily on fish, but also on crustaceans and cephalopods (octopuses). Individual dives may last a few minutes, partially correlated to water depth. Foraging may be solitary or take place in groups of up to several hundred birds, when synchronized diving can occur. A foraging trip normally consists of a series of dives over a period of an hour or more, interspersed with rest periods on the sea surface. Prey is usually swallowed underwater, but large prey items may be brought to the surface, presumably to make them easier to swallow.

The imperial cormorant appears to have few natural enemies, although skuas *Catharacta* spp. may snatch eggs or small chicks from inadequately guarded nests. The species is susceptible to human disturbance, when temporarily deserted nests will often loose their contents to aerial predators. It is also susceptible to oiling and there are records of birds drowning in fish traps and nets.

The *"atriceps"* cormorant group is usually recognized as consisting of seven taxa, each of which is considered in detail to follow.

Blue-Eyed Cormorant *P. [atriceps] atriceps*

This taxon is restricted to southern Argentina and Chile and to the Falkland Islands. The Falklands population (which has also been described as belonging to *P. [atriceps] albiventer* and is sometimes called the king cormorant) has been estimated as between 45,000 and 84,000 breeding pairs, representing 135,000 to 252,000 birds. "Albiventer" may be distinguished from the majority of South American birds by having black instead of white cheeks, giving it a black-faced appearance. However, the forms co-occur in South America, where mixed pairs have been observed, resulting in the black-faced albiventer birds being considered a colour-morph of a polymorphic taxon and not a distinct taxon of its own.

The Falklands population breeds in densely packed colonies of up to several hundred pairs on flat cliff tops, often associated with rockhopper penguins *Eudyptes chrysocome* and black-browed albatrosses *Thalassarche melanophrys*. Breeding takes place from October to February. Outside the breeding season, birds use breeding sites as roosts. The taxon forages on small fish and crustaceans in large flocks, notably in winter when not breeding.

The blue-eyed cormorant coexists on the Falklands with the rock cormorant or shag *P. magellanicus,* which is smaller in size, and usually forages singly in shallower, more inshore waters among kelp beds. The Falklands population (the species is also found in South America) has been estimated as 32,000 to 59,000 pairs. It breeds in the austral summer (September to February) in small colonies on cliff ledges. The rock cormorant may be told apart from all *atriceps* cormorants by its red, not orange, bare facial skin that extends around the eye, and an all-black head and neck save for a white cheek patch. In breeding plumage the crest is noticeably smaller than that of the imperial group of cormorants.

All the other *atriceps* cormorant taxa are the sole breeding representatives of their family where they occur, so their identification is unproblematic.

Antarctic Cormorant *P. [atriceps] bransfieldensis*

The Antarctic cormorant is found on the Antarctic Peninsula and on the South Shetland Islands, and is thus endemic to the Antarctic Treaty area. It is the most southerly breeding cormorant, and, indeed, the most southerly member of its order. This taxon is among the largest of the *atriceps* group of cormorants, reaching 3.25 kg in mass. Antarctic cormorants are white-faced, with the white cheek line extending to or above the eye, distinguishing them from the Falklands Islands' blue-eyed cormorants. Its population has been estimated at 40,000 birds. The species appears to be sedentary in the main, although local movements occur to seek out open water.

The taxon breeds colonially, in colonies, often of 20–40 pairs but sometimes larger—729 nests were counted in 1985 in one colony on Cormorant Island, near the United States' Palmer Station on Anvers Island. Breeding colonies are often intermixed with those of pygoscelid penguins, especially the chinstrap *Pygoscelis antarctica* and the gentoo *P. papua*. Foraging in shallow waters occurs singly or in small flocks. Diet consists of fish, mainly Antarctic rock cod of the family Nototheniidae, cephalopods, and crustaceans, such as isopods and euphausiids (krill). Interestingly, clear patterns in timing of foraging occur, with males and females being away from nests during different time periods.

The Cormorant Island population was severely affected by an oil spill in 1989, leading to a local population decline from about 970 pairs to 165 pairs in 1996. Mass chick starvation has been observed, leading to low breeding success at times. Population declines since the 1980s have been recorded at several other sites within the taxon's range, with changes in abundance of juvenile year-classes of prey fish suggested as the cause.

South Georgia Cormorant *P. [atriceps] georgianus*

As is to be expected from its common name, this taxon occurs on the sub-Antarctic island of South Georgia. It also breeds on the Shag Rocks in the Scotia Sea, and on the maritime Antarctic South Orkney Islands and South Sandwich Islands. However, some accounts place the South Sandwich and South Orkney populations with the Antarctic cormorant. The South Georgia cormorant is very similar in appearance to the Antarctic cormorant, but the white cheeks do not extend quite as high, with the line of demarcation from the black cap passing through the ear coverts rather than reaching the eye. The taxon's total population has been variously estimated as 20,000 birds and 7500 to 11,000 pairs. Perhaps 1000 pairs occur on the isolated Shag Rocks and 2000 pairs at the South Orkneys, with the larger South Georgia population estimated as 4000 pairs. The South Sandwich Islands' population is not well surveyed but has been said to be between 100 and 1000 pairs in size. In 1997, only an estimated 265 pairs were found on two of the islands in the group (Montagu and Bristol), with a colony of about 100 pairs on a third island (Zavadoski) found previously apparently no longer present.

The South Georgia cormorants breeds in often small colonies (less than 100 pairs) on sea cliffs and islets in the austral summer, laying two to three eggs in November–December. It is a sedentary taxon, foraging solitarily or in small groups in shallow, inshore waters on nototheniid fish. In whaling and sealing days South Georgia cormorants were sometimes taken for food, but are now largely unthreatened.

Crozet Cormorant *P. [atriceps] melanogenis*

The Crozet cormorant occurs on two island groups approximately 950 km apart in the southern Indian Ocean: South Africa's Prince Edward Islands and the French Îles Crozet. This taxon is one of the black-faced forms of the imperial cormorant. The total population was estimated as 1500 pairs in 1980s, placing it (along with the Heard and Macquarie cormorants) among the rarest forms of the imperial cormorant. At the Prince Edward Islands the population on the larger Marion Island has declined with numbers of breeding pairs dropping by 68% from 841 in 1994–1995 to 272 in 2002/2003. During this period breeding success has generally been too low to sustain the population, with mortality of chicks attributed to starvation. The population on little-visited and smaller Prince Edward Island was 120 pairs in 1984 but only 50 pairs in 2001. These decreases have coincided with a period of warming that is thought to have affected the cormorant's prey (primarily nototheniid fish, but also octopuses and the shrimp *Nauticaris marionis*). The Îles Crozet population was estimated as 815–835 pairs in 1981–1982.

At Marion Island birds breed on coastal cliff tops and offshore rocks in small colonies, mainly in summer, although winter breeding has been reported. Breeding sites are also used as winter roosts by nonbreeding birds. Foraging occurs singly or in small groups, mainly among the kelp beds close inshore. Crozet birds may forage up to 6 km from shore.

There are no records of banded birds moving between the two island groups, so the Prince Edward and Crozet populations would appear to be reproductively isolated (and may thus be genetically distinct). At the Prince Edward Islands all cormorant colonies have been zoned as Special Entry Areas from 2005, with entry (within 100 m of nests) allowed under permit issued for monitoring and research purposes only. (This measure was taken to reduce human disturbance since Subantarctic skuas are known to take eggs and small chicks from unattended nests.) However, it seems doubtful that this action will be sufficient to reverse the population's decline. If a genetic study resulted in the Crozet cormorant attaining specific status, there seems little doubt it would be awarded the threatened category of Endangered.

Kerguelen Cormorant *P. [atriceps] verrucosus*

This taxon is restricted to Îles Kerguelen, a French sub-Antarctic possession in the southern Indian Ocean. Kerguelen is the largest of the sub-Antarctic island groups, and probably as a consequence supports a large cormorant population, variously estimated as 30,000 to 35,000 birds, and as 10,000 to 12,000 pairs in the mid-1990s. The population appears to be stable. The Kergeulen cormorant is the smallest of the taxa within the imperial cormorant complex, with a length of 65 cm and a mass reaching only 2.2 kg. The bill is noticeably slender and short. The Kergeulen cormorant is black-faced and most birds lacks the white wing bar common the other forms, making it overall the darkest taxon. Birds with white in their wings occur only in eastern parts of Kerguelen and it has been hypothesized their recent presence might suggest the arrival of individuals from other island groups in the southern Indian Ocean. However, there have been as yet no genetic studies published to check this idea. The species is sedentary, although there are local movements reported from within the island group. Single records of birds from Western Australia and Heard Island are known or thought to be ship-assisted.

Breeding colonies may be large (up to 400 nests) in the eastern part of the island, but small colonies of three to thirty pairs are more usual.

Birds forage in sometimes large groups, mainly in the sheltered bays that are common along the island group's heavily indented coastline. However, there are records of juveniles 80 km from land, reflecting the large area of shallow water, equivalent to a continental shelf (required for a bottom feeder), which is absent at other sub-Antarctic islands.

Heard Cormorant *P. [atriceps] nivalis*

The Heard Cormorant is found only at the Australian Heard Island in the southern Indian Ocean. It has not been recorded at nearby McDonald Island 40 km away. This is a large member of the imperial group, weighing as much as 3.3 kg. It is a white-faced taxon, in appearance more similar to the Antarctic and South Georgian taxa than to those occurring on the geographically closer sub-Antarctic islands of the southern Indian Ocean.

The island's total population was thought to be no more than 1000 birds, with the breeding population fluctuating from 90 to 200 pairs. However, in 2000–2001 a new colony was discovered at Cape Pillar on the remote and rarely visited southwestern side of the island, containing about a thousand nests. Previously only three much smaller breeding sites were known. Thus has suggested that the total population is more of the order of 2500 to 3600 birds. The discovery of the Cape Pillar colony explains earlier (and puzzling) observations of up to 600 roosting birds, which far exceeded the then estimates of the total size of the breeding population.

This is a little-studied taxon. Diet is broadly similar to those of the other forms of the imperial cormorant group: fish, cephalopods, and crustaceans, especially polychaetes, with birds foraging by pursuit diving close inshore.

Macquarie Cormorant *P. [atriceps] purpurascens*

The most easterly of the imperial cormorant taxa, the Macquarie cormorant occurs only at the Australian Macquarie Island and the Bishop and Clerk Islets 33 km to the south. The latter population may be an isolated one. The taxon is a large, black-faced form, considered most closely related to the Crozet and Kergeulen cormorants. The taxon's total population has been recently estimated as 3750 birds with 1250 breeding pairs. In the 1970s, the total population was put at 760 pairs. Perhaps 100 pairs occur at Bishop and Clerk Islets, although census data are sparse. Twenty-three breeding colonies are known (3–320 nests), not all active every year, and breeding numbers fluctuate annually.

The diet consists mainly of fish, but also crustaceans and polychaetes, caught by solitary diving during the summer breeding season, although small foraging flocks of up to forty birds may form in winter months, diving simultaneously.

Birds have been killed by collision with aerials, and chicks have been killed by Subantarctic skuas and possibly by feral cats *Felis catus,* now thankfully eradicated from the island. Breeding failure sometimes follows heavy storms. Indeed, the whole imperial cormorant group is at risk from losing nests and their contents to bad weather, as all taxa breed close to the water's edge. Rough seas may also inhibit foraging by breeding birds, leading to starvation of chicks and lowered breeding success. Poor weather and changes in food supply are most probably the driving forces behind the large population fluctuations that have been observed at many breeding localities, both at Macquarie and elsewhere.

The larger and all-dark Great Cormorant *P. carbo* has been recorded more than once as a nonbreeding vagrant at Macquarie Island. This species breeds in both Australia and New Zealand, so either may be the source.

JOHN COOPER

See also **Antarctic Peninsula; Birds: Diving Physiology; Black-Browed Albatross; Chinstrap Penguin; Crested Penguins; Crozet Islands (Îles Crozet); Fish: Overview; Gentoo Penguin; Heard Island and McDonald Islands; Kerguelen Islands (Îles Kerguelen); Macquarie Island; Prince Edward Islands; Skuas: Overview; South Georgia; South Orkney Islands; South Sandwich Islands; South Shetland Islands; Sub-Antarctic Skua; Zooplankton and Krill**

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COSMIC MICROWAVE BACKGROUND RADIATION

The Cosmic Microwave Background Radiation (CMBR) is broadband radio emission from the early universe. Its brightness as a function of frequency is a nearly perfect blackbody or Planck curve that increases with frequency up to 168 GHz and declines exponentially at higher frequencies. The blackbody temperature characterizing the radiation is 2.7 K. The CMBR was emitted by normal matter about 400,000 years after the Big Bang, some 13 billion years ago, at the "time of recombination." Previous to the time of recombination, electrons and ionized nuclei were embedded in an all-pervading sea of photons, similar to the interior of the Sun. At the time of recombination, the electrons and nuclei combined to form atoms, allowing the sea of photons to stream freely through a now nearly transparent universe. After billions of years, those photons, highly redshifted by the universal cosmic expansion, have become the CMBR we see coming from all directions today.

The CMBR was first observed by Arno A. Penzias and Robert W. Wilson at Bell Laboratories at Crawford Hill, New Jersey, in 1964. Cosmologists soon recognized that the existence of the CMBR was strong evidence for the Big Bang theory, and that further observations should show small departures from a perfect blackbody curve, as functions of direction on the sky, frequency, and polarization. These departures, or anisotropies, result from small irregularities in the early universe, the same irregularities that eventually evolved into stars and galaxies. Thus began a new field of observational cosmology, the quest to detect and study CMBR anisotropy. This goal was vigorously pursued by many scientific groups for decades, but there was little initial success. It became clear that the anisotropies were very small, about one part in a million, and that noise in the data caused by fluctuations in the Earth's atmosphere was a serious problem when making the observations. CMBR instruments were placed on high mountain sites, in balloons, and on satellites in space. By 1992, the Cosmic Background Explorer (COBE) satellite launched by NASA detected CMBR anisotropy by comparing patches of sky that were separated by angles of 7° or more. This is "large scale" anisotropy, and its measurement provides information about primordial physics. This was just the beginning. Measurement of anisotropies on smaller scales could provide information on the ultimate fate of the universe, the mechanism of galaxy formation, and unknown physics. Of particular interest is the increase in CMBR fluctuations at a scale size of 1° on the sky, which are created by gravity-driven sound waves at the time of recombination and are therefore known as the acoustic peak. The Sunyaev-Zel'dovich effect occurs when CMBR photons are scattered by foreground clusters of galaxies, resulting in anisotropies at scales of 0.03°. The CMBR is also slightly polarized, and the way in which it is polarized can distinguish between different theories of the early universe. Small-scale measurements require large telescopes that would be expensive, perhaps prohibitively expensive, to launch into space. Scientists therefore searched for the best possible telescope sites on the Earth's surface, and that search led to Antarctica.

The Antarctic Plateau is an exceptionally good site for CMBR observations. The altitude is fairly high, but more important are the cold temperatures and the low level of absolute humidity. The dominant source of error in ground-based CMBR measurements is thermal radio emission from irregular blobs of atmospheric water vapor being blown across the aperture of the telescope by the wind. This is called sky noise. Less water vapor and colder water vapor both result in less sky noise and hence more accurate measurements. Cold air can hold only a little water vapor. Air at the freezing point of water (0°C) can hold over 80 times more water than air at the South Pole's average annual temperature of –49°C. The amount of water vapor in a column of air extending through the entire atmosphere is measured by the precipitable water vapor (PWV), the amount of rain that would fall if all the water vapor within that column were somehow turned into rain. The average level of PWV at the South Pole in the winter is 0.25 mm. This compares to 1.65 mm at the top of Mauna Kea in Hawaii (an excellent high-altitude observatory site), and several centimeters at a typical place on the Earth's surface. The South Pole is an excellent site for CMBR observations, and higher locations on the Antarctic Plateau are probably better still.

The first attempt at CMBR observations from the Antarctic Plateau was an expedition to the South Pole in December 1986 by Mark Dragovan, Antony A. Stark, Robert Pernic, and Martin A. Pomerantz, under the sponsorship of the US Antarctic Program with support from Bell Laboratories. No CMBR anisotropies were observed, but sky noise and opacity were measured. The results were sufficiently encouraging that in the Austral summer of 1988–1989, three CMBR groups led by M. Dragovan, Jeffrey Peterson, and Philip Lubin participated in the "Cucumber" campaign, where three Jamesway tents and a generator dedicated to CMBR anisotropy measurements were set up at a temporary site 2 km from Amundsen-Scott Station. These were summer-only campaigns, where instruments were shipped in, assembled, tested, used, disassembled, and shipped out within a single three-month-long summer season. Considerable time and effort were expended in establishing and then demolishing observatory facilities, with little return in observing time. What little observing time was available occurred during the warmest and wettest days of midsummer.

Wintertime observations became possible with the establishment in 1990 of the Center for Astrophysical Research in Antarctica (CARA), a National Science Foundation Science and Technology Center. CARA developed year-round observing facilities in the "Dark Sector," a section of Amundsen-Scott South Pole Station that is dedicated to astronomical observations. CARA scientists fielded several CMBR instruments: White Dish, Python, Viper, Arcminute Cosmology Bolometer Array Receiver (ACBAR), and the Degree-Angular Scale Interferometer (DASI). By 2001, data from these instruments, together with Boomerang (Balloon Observation of Millimetric Extragalactic Radiation and Geophysics), a CMBR experiment on a long-duration balloon launched from McMurdo Station on the coast of Antarctica, showed clear evidence for the acoustic peak in the

CMBR anisotropy at an angular scale of 1°. This is interpreted to mean that the overall geometry of the universe is flat, as opposed to being positively or negatively curved. Soon thereafter, this result was confirmed and improved by the Wilkinson Microwave Anisotropy Probe (WMAP) satellite launched by NASA. In 2002, the DASI group led by John E. Carlstrom reported the detection of polarization in the CMBR. These observations strongly support a "Standard Theory" of cosmology, where the dynamics of a flat Universe are dominated by forces exerted by the mysterious Dark Energy and Dark Matter.

CMBR observations continue on the Antarctic Plateau. The South Pole Telescope (SPT) is a 10 m diameter offset telescope designed to measure anisotropies on scales much smaller than 1°, especially the Sunyaev-Zel'dovich effect. This is a scattering of CMBR photons by hot electrons in clusters of galaxies. It is an efficient way to discover clusters of galaxies at high redshift, which are otherwise difficult to detect. A comprehensive survey of galaxy clusters is planned using the SPT, with the aim of better understanding Dark Energy.

ANTONY A. STARK

See also **Amundsen-Scott Station; Antarctic: Definitions and Boundaries; McMurdo Station; South Pole; United States: Antarctic Program**

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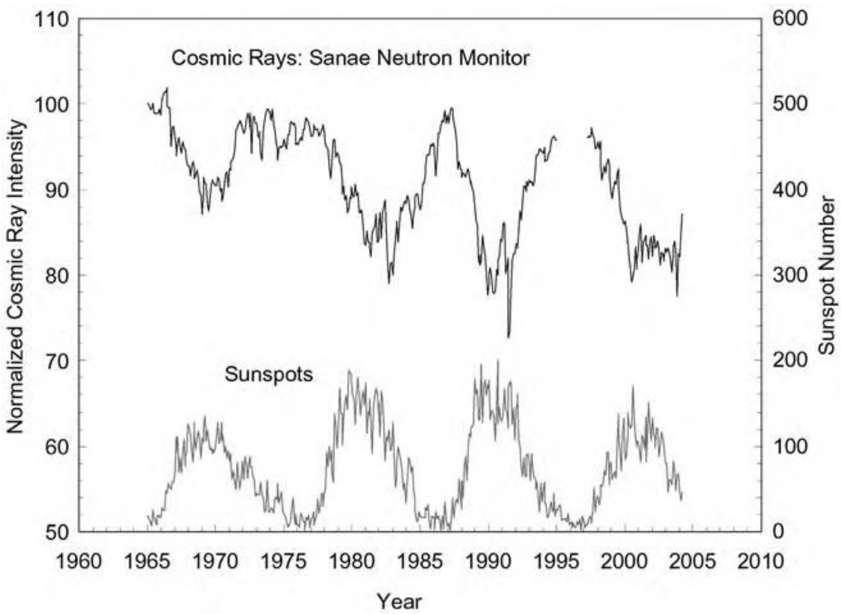
COSMIC RAYS

Introduction

Cosmic rays are charged particles—not rays—coming from the cosmos. They are characterized by extremely high energies. This radiation was discovered by Victor Hess on his famous balloon flights in 1912, when he found that the "natural background radiation" increased with altitude, against his expectation that it would decrease as he moved farther away from the presumed radiation sources inside the Earth. It took until the mid-1930s to establish unambiguously that these "rays" were particles, and it has subsequently been learned that they consist about 90% of protons (H nuclei) and 9% alpha particles (He nuclei). The remaining percent or so is made up of heavier nuclei, electrons, and positrons. This composition is very similar to that of "ordinary," low-energy matter in thermal equilibrium in the universe.

Cosmic ray energies are indeed extremely high. Particles with energies higher than one million (10^6) electron volts (eV) are generally classified as cosmic rays. Cosmic rays with energy in excess of 10^{20} eV have been detected. The number of cosmic rays decreases with increasing energy, and only a few of these 10^{20} eV particles have been observed. In more common units, an amount of energy of 10^{20} eV is equivalent to about 10 joules (J). To get a feeling for these numbers, a 100 watt (W) light bulb uses 100 J of electricity per second, the metabolism of the human body is a 100 W machine, and a small ball weighing 50 grams and flying at 100 km per hour has about 2000 J of energy. Against these numbers, 10 J of energy in a cosmic ray does not sound like much, but bear in mind that this energy is all concentrated into one single elementary particle, instead of the 10^{24} particles or so contained in the ball! Another way to look at this is that this energy is about one million times higher than can be achieved with the largest particle accelerators. This implies extremely efficient acceleration mechanisms in the cosmos, and one of the prime aims of cosmic ray research is to find the sources that can do this. During the last 30 years it has become ever better established that cosmic rays with energies up to 10^{15} eV are accelerated by the blast waves of supernova remnants in our own galaxy, while those with higher energies have been accelerated several times by such remnants, or may come from other galaxies.

It is difficult to pinpoint these cosmic ray sources because cosmic ray astronomy is fundamentally different from the well-known optical astronomy, and its



Count rate of the SANAE neutron monitor, with the number of spots on the surface of the sun.

more general cousins of radio, x-ray, and gamma ray astronomy. In the latter cases, the electromagnetic waves or photons travel in straight lines from the source to the observer. Thus, when one sees light from a certain direction, one knows where the source of that light is, and from the brightness and color of that light (intensity and frequency), one can immediately start to analyze the properties of the source. For cosmic rays this is different, because the universe is pervaded by magnetic fields: the geomagnetic field around the Earth, a heliospheric magnetic field that is set up by the Sun and blown away for several 100 Sun-Earth distances by the solar wind. (One Sun–Earth distance is called an astronomical unit, or AU.) Beyond that, there is an interstellar or galactic magnetic field, while there is even an intergalactic field between individual galaxies. According to the standard theory of magnetism, the charged cosmic ray particles spiral around these magnetic field lines. This corkscrew motion makes them slide along the magnetic field direction, while they cannot readily move in directions across the field. Since these fields are random, the cosmic rays get scattered, and once they arrive at Earth, their arrival direction has become entirely unrelated to the direction of their source. This means that the origin and properties of cosmic rays must be unraveled differently, and this is primarily done by measurement and study of (1) their energy spectrum (i.e., the number of cosmic rays as function of their energy); (2) their composition, which is the number of cosmic rays of different type; and (3) their anisotropy, which is the number of cosmic rays as function of direction in the sky.

Cosmic ray experiments in Antarctica can be divided into two categories: experiments at high energies that basically search for the sources of cosmic rays in the galaxy, and those at lower energies that study the propagation of cosmic rays in the heliosphere and the geomagnetic field. This second category will be discussed first.

Cosmic Ray Modulation Studies with Neutron Monitors

The counts of the SANAE neutron monitor show that the cosmic ray intensity at these lower energies, typically from 10^9 to 10^{10} (one billion to 10 billion) eV, varies with time. It has become well established that this variation is in response to solar activity. The Sun's atmosphere is so hot, with a temperature of about 10^6 degrees, or equivalent particle energy of about 100 eV, that it blows away supersonically at 400 km/s, and is called the solar wind. (Notice, however, that this solar wind energy is so low that the particles do not nearly qualify to be called cosmic rays.) The Pioneer 10 and Voyager 1 and 2 spacecraft have observed this wind up to 100 AU from the Sun. Since it is fully ionized, a state of matter that is called a plasma, this wind carries the solar magnetic field with it, and this solar plasma and magnetic field set up a region around the Sun that is called the heliosphere. Cosmic rays must work themselves in along this outward moving field to be observed at Earth. The plasma and field properties vary with time, with the dominant variation being an 11-year cycle, as observed for instance by the number of sunspots. It indicates that when solar activity is high, the cosmic ray intensity is low and vice versa. This 11-year cycle is also seen in the wind speed and strength of the magnetic field in the heliosphere. Thus, the cosmic ray intensity varies opposite to solar activity because when the Sun is active and the heliospheric field strong and turbulent, it is more effective to keep the cosmic rays away from the inner parts of the heliosphere (and Earth). This process is called heliospheric modulation of the cosmic ray intensity.

The neutron monitors that record this modulation process are large proportional counters, almost 2 m long and 15 cm in diameter, embedded in lead and wax (or polyethylene) boxes. They were designed in the late 1940s by John Simpson of the University of Chicago, and they work as follows: When a cosmic ray strikes the atmosphere, it breaks up the nuclei of air molecules to form secondary particles, so that deep inside the atmosphere one ends up with a shower of secondaries from the single cosmic ray. Some of these secondaries are neutrons. These neutrons are captured in the $^{10}BF_3$ gas inside the proportional counter to produce electrically charged alpha particles, which are attracted to the high voltage wire of the counter, and are registered electronically. The neutrons will, however, be captured in the gas of the counter only if they are slowed down. This is achieved by the wax/polyethylene around the counter. The detection efficiency for neutrons is only a few percent, so there is also a lead ring around the counter that produces up to ten additional neutrons for each one striking a lead nucleus. In this way, a neutron monitor registers approximately one count for every cosmic ray hitting it. Neutron monitors can have up to twenty of these counters, and because of the lead, they are massive, at about 3 tons per counter.

There are approximately forty of these neutron monitors around the Earth that measure variations in the cosmic ray intensity. Of these, eleven are in the Southern Hemisphere, with six in Antarctica. These six are Larc, Mawson, McMurdo, SANAE, South Pole, and Terre Adelie.

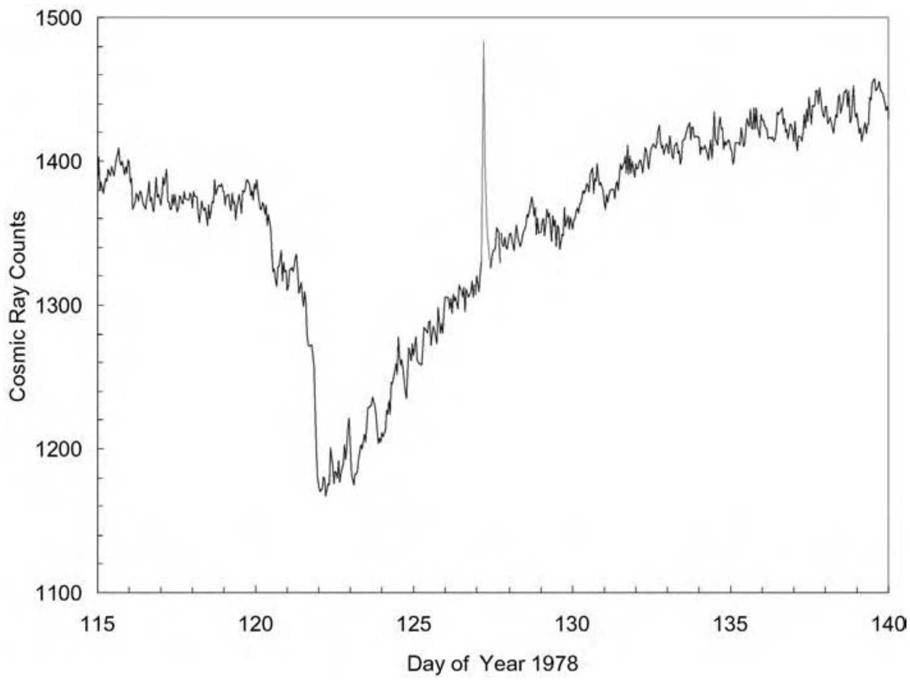
The French group also operates a neutron monitor on sub-Antarctic Îles Kerguelen (49°35′ S, 70°22′ E). Apart from these currently operating neutron monitors, the following Antarctic ones existed for some time since the early 1960s: Cape Hallet (USA), Casey/Wilkes (Australia/USA), Ellsworth (USA), General Belgrano (Argentina), Mirny (USSR/Russia), Syowa (Japan), and Vostok (USSR/Russia).

The form of the geomagnetic field is the primary reason for placing neutron monitors in Antarctica. This field is dipole-like, and it becomes more radial with increasing latitude away from the equator. This means that cosmic rays "slide in" easier along this field in the polar regions than at lower latitudes, leading to more low energy particles at the poles. These low energy particles are more subject to variations in the solar and heliospheric parameters, leading to larger modulation effects. This is a good example of why the polar regions are appropriately called "windows into geospace."

Apart from the 11-year modulation, there are also shorter-term changes in the cosmic ray intensity. The graph shows the variations seen on the SANAE neutron monitor from April 25 (day 115) to May 20 (day 140) in 1978. The big decrease commencing on days 120 to 122, and resetting subsequently, is called a Forbush decrease. Such an event happens when an active region on the surface of the Sun erupts to release an intense cloud of plasma and field, in a so-called Coronal Mass Ejection (CME). The strong magnetic field inside this blob can keep the cosmic rays out of its interior. It propagates away from the Sun at about twice the solar wind speed, and when it engulfs Earth after about 2 days, the cosmic ray intensity suddenly decreases. As the CME recedes beyond the orbit of Earth, the intensity resets again. These Forbush decreases occur, on average, once per month, with a higher frequency towards solar maximum.

Sometimes these solar eruptions and their accompanying fields are so intense that they can accelerate the available pool of solar particles to cosmic ray energies. Such an event is shown by the sharply pointed spike on May 7 (day 127). It is called a Ground

Station	Lat.	Long.	Alt(m)	Opened	Operator
Larc	62°12′09″ S	58°57′42″ W	40	1991	University of Rome, Italy
Mawson	67°36′17″ S	62°52′15″ E	15	1957	Australian Antarctic Division
McMurdo	77°50′53″ S	166°40′06″ E	48	1960	Bartol Research Institute, USA
SANAE	71°40′25″ S	02°49′44″ W	856	1964	Northwest University, South Africa
South Pole	89°59′51″ S	139°16′22″ E	2820	1964	Bartol Research Institute, USA
Terre Adelie	66°39′46″ S	140°00′05″ E	32	1967	L'Observatoire de Paris, France



Short term cosmic ray variations (a, Forbush decrease, a Ground Level Enhancement and diurnal variations) observed by the SANAE neutron monitor.

Level Enhancement (GLE). In these events the particles are created by our own sun, and are therefore called solar cosmic rays. They are studied intensely with neutron monitors because the Sun is the only object near enough so that one can literally look into the face of the source. The Sun is a very weak source, however, because these GLEs invariably die out within a day, and since 1942 only sixty-nine of them have been observed. The strongest one was on 23 February 1956, and the second strongest one was on 20 January 2005. These events are usually highly anisotropic, which means that the particles come towards us in well-defined beams. To unravel the size, intensity, direction, and energy of these beams requires that one must have simultaneous observations from several neutron monitors. Polar neutron monitors are particularly well suited for this because they preferentially register the low energy particles as previously mentioned. In addition, these polar neutron monitors also tend to look into better defined, narrower regions of space than the ones at lower latitudes. With this in mind, the Bartol Research Institute, in collaboration with Russian and Australian scientists, operates Spaceship Earth, a network of eleven polar neutron monitors that is designed to study these events optimally. Spaceship Earth consists of the South Pole, McMurdo, and Mawson neutron monitors, plus eight neutron monitors in the Arctic.

Diurnal variations of amplitude of about 1% are due to the Earth's rotation on its axis, which causes the neutron monitor to look into and away from the beam once per day. Careful analysis of these small, almost insignificant variations over a period of more than 40 years has yielded valuable information about the propagation conditions of cosmic rays in the heliosphere.

Apart from the neutron monitor stations listed above, the Bartol Research Institute and the Australian Antarctic Division also jointly operate a mobile neutron monitor on annual voyages by vessels of the US Coast Guard, from the US west coast to McMurdo in Antarctica. The purpose of these so-called latitude surveys is primarily to measure the energy response of neutron monitors, which is needed to unfold and interpret the observed variations.

Other Modulation Experiments

The Antarctic ice sheet offers an ideal opportunity to study the intensity of cosmic rays backwards in time, before the advent of the technological era in the middle of the twentieth century. One of the secondaries produced by cosmic rays when they strike atmospheric nuclei is ^{10}Be, an isotope of the element beryllium. This ^{10}Be is not produced in significant quantities by other processes. It filters out to the surface within about a year and gets lost, except in polar ice where it is perfectly preserved for hundreds of thousands of years. This ^{10}Be concentration is a signature of the cosmic ray intensity back into the past, and it can be recovered from ice cores drilled by several international collaborations, up to 3 km deep at locations such as South Pole, Kohnen, Dome C, Dome Fujii, Vostok, and Byrd. The results from South Pole and Vostok have shown that the cosmic ray intensity has always been variable, and that there were extensive periods in the last 1000 years where it was much higher than at present. This, in turn, implies a lower solar activity during these periods. This cosmic ray/^{10}Be record therefore enables one to study helioclimatology in the distant past.

The modulation process is also studied with a variety of other particle detectors, on Earth as well as in space. Space detectors have the advantage that they observe the cosmic rays directly and can record different species separately, while they are also sensitive to lower energies. Neutron monitors, however, provide a much longer and more stable baseline, while their higher count rates allows for more detailed studies of small effects. Another type of detector that is used inside the atmosphere is the so-called muon telescope, one of which is operated by the Australian Antarctic Division at their Mawson station. These muon telescopes are actually older than neutron monitors, originating in the early 1940s. They consist of stacked proportional counters or scintillation detectors in several layers, and their electronics is set up in such a way that two or more counters in different layers must be triggered simultaneously. This allows for the reconstruction of the direction of arrival of the detected particle and, therefore, of the original cosmic ray. These muon telescopes are sensitive to about 10 times higher energies than neutron monitors, especially when they are placed underground, because the additional overburden filters out the lower energy particles. Consequently, heliospheric modulation effects are much smaller on these muon telescopes, and they are more effective to "look through" the heliosphere, straight into the galaxy, to study arrival directions of cosmic rays from their sources.

Cosmic Ray Source and Composition Studies

Cosmic ray source studies are, however, more actively pursued with so-called air shower and neutrino detectors. There is one such air shower detector in Antarctica, at the Amundsen-Scott base at South Pole. Air shower detectors measure a variety of secondary particles caused by cosmic rays in the atmosphere. Like the muon telescope, they are scintillation detectors, producing light flashes when the particles interact with the scintillator, and this light is detected by photomultipliers. They are built in units of a few square meters each, and these units are not stacked on top of one another as with the muon telescope, but they are arranged in patterns covering several square kilometers. When more than one of these horizontally separated detectors is triggered simultaneously, it means that the particles should be secondary products of a single cosmic ray. The number of triggers and the distance between the triggered units indicate the energy and type of the original cosmic ray particle, while any small time differences that may exist between the individual hits indicate the direction from which the particle came. This information about the energy spectrum and the direction enables one to study the sources of cosmic rays and their propagation through the galaxy and the intergalactic medium. Currently there are about ten of these large air shower experiments around the world. The largest one is the Pierre Auger experiment in Argentina, in which the detectors are spaced over an area of 3000 km^2. It is sensitive to the very highest energies at about 10^{20} eV, and it is about to deliver its first results.

The South Pole Air Shower Experiment (SPASE) at the Amundsen-Scott base at South Pole started in 1987 as a collaborative project between the Bartol Research Institute of the University of Delaware and the University of Leeds in the UK. It was upgraded in 1995 to its current configuration of 120 scintillators, spread over an area of 16,000 m^2. This is much smaller than the Auger experiment, which means that it is sensitive to cosmic rays of much lower energy, between 10^{12} and 10^{14} eV. A big advantage of its unique location is that at the pole sources always maintain the same altitude—they don't "rise" and "set." This is one of the reasons why this experiment makes an important contribution to unraveling cosmic ray composition and sources in this crucial energy range.

An entirely different way to study cosmic rays in the same energy range is with balloon experiments. An example is the Cosmic Ray Energetics and Mass (CREAM) experiment, in a collaboration led by scientists of the University of Maryland. Because these balloons fly near the top of the atmosphere, they can detect the original cosmic rays before the rays interact with the atmosphere. The CREAM instrument consists of detectors that can simultaneously measure cosmic ray energy, charge and species, ranging from protons to iron. Once again, these measurements are designed to study the acceleration and propagation of cosmic rays in the galaxy. The first CREAM experiment was launched from McMurdo in December 2004 on a Long Duration Balloon (LDB) flight, setting a record for such balloons with three circumpolar passes in 42 days. An earlier series of balloon experiments of the same kind was the Japanese-American Collaborative Emulsion Experiment (JACEE), with launches in Antarctica between 1990 and 1995. In yet another US–Japanese joint project, the Balloon-borne Experiment with a Superconducting Spectrometer (BESS) searches for antimatter in the cosmic radiation and measures energy spectra of less exotic components. After nine successful previous launches, this collaboration also had their first 8-day-long Antarctic launch from McMurdo in December 2004.

Another big advantage of SPASE is its proximity to the Antarctic Muon and Neutrino Detector Array (AMANDA), which is the world's largest muon and neutrino telescope, also at the Amundsen-Scott base. Neutrinos are produced by the decay of radioactive elements and particles, such as pions, in the cosmic ray showers. They are very light, with a mass of less than one millionth of an electron, they are uncharged, and they have almost no interaction with matter. This makes them unique messengers of the cosmos because they can travel across the universe with the minimum interference of matter and magnetic fields. They are studied to answer questions about their own properties such as their mass, their oscillation between different types, and their contribution to the so-called missing mass in the universe. But their elusiveness also makes them extremely difficult to detect, and immense instruments are required. To achieve this, the scintillation process is again used, but the scintillator is supplied by nature, in the form of clear and transparent polar ice. When a neutrino crashes into an atom of this ice, it produces a muon, which is detected by a photomultiplier through the light it produces, just as in the muon telescopes and air shower experiments. Once again, directions are preserved, which means that projections back to the source can be made. However, only about one in a million of these muons is produced by neutrinos. The others come from cosmic ray showers produced in the atmosphere. To suppress this atmospheric background, the neutrino detector must be several kilometres deep. In addition, the electronics are set up to make it look downwards instead of up, so that it actually looks for muons that are produced by neutrinos that come from the North Pole direction, and that have a reasonable opportunity to interact as they move through the entire Earth.

AMANDA is sensitive to neutrinos with energy up to 10^{12} eV. It is an international collaboration comprising nineteen participating institutions, led by scientists of the University of Wisconsin. Construction began in the early 1990s and it was subsequently upgraded to AMANDA II. Its 700 photomultipliers hang between 1500 and 2000 m below the ice, like beads on nineteen strings that are 2 km long. The diameter of the string array is 200 m, which means that the array fills an effective volume of about 15,000,000 m^3.

So far, AMANDA has not seen any of these cosmic messengers, but has only detected neutrinos produced by cosmic rays in the atmosphere. For this reason, the AMANDA and SPASE experiments are presently upgraded into the much larger IceCube/IceTop experiment. IceCube will view one cubic kilometre of ice with 5000 photomultipliers, making it about 60 times larger than AMANDA, while IceTop will be a 1 square kilometre air shower detector on the surface. The first IceCube string was lowered in January 2005.

HARM MORAAL

See also **Amundsen-Scott Station; ANARE/ Australian Antarctic Division; Antarctic Ice Sheet: Definitions and Description; Astronomy, Neutrino; Geomagnetic Field; Geospace, Observing from Antarctica; Ice-Core Analysis and Dating Techniques; Kerguelen Islands (Îles Kerguelen); Magnetosphere of Earth; McMurdo Station; Solar Wind; Vostok Station**

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COUNCIL OF MANAGERS OF NATIONAL ANTARCTIC PROGRAMS (COMNAP)

The Council of Managers of National Antarctic Programs (COMNAP) brings together the National Antarctic Programs from twenty-nine countries: Argentina, Australia, Belgium, Brazil, Bulgaria, Canada, Chile, China, Ecuador, Finland, France, Germany, India, Italy, Japan, The Netherlands, New Zealand, Norway, Peru, Poland, Russia, South Korea, South Africa, Spain, Sweden, Ukraine, the United Kingdom, the United States, and Uruguay. Two more countries—Estonia and Romania—are currently in the process of joining.

COMNAP is a council of managers and operators that, under the Antarctic Treaty System, helps oversee operational implementation, safety, technology, and information sharing. It provides the Antarctic Treaty, on request, technical advice developed using members' pool of expertise.

National Antarctic Programs are those agencies tasked by their governments to implement and manage national activities in Antarctica, including organising expeditions. While most of these activities focus on the support of scientific research, they also contribute to the governance and environmental protection of the Antarctic under the auspices of the Antarctic Treaty.

The National Antarctic Programs had their foundation in several early exploring and scientific expeditions that had international components. The most notable of these were in the closing years of the nineteenth century. The Belgian Antarctic expedition aboard *Belgica* (1897–1899), under Belgian Adrien de Gerlache, was the first to winter in the Antarctic, which was done aboard ship. The British Antarctic expedition aboard *Southern Cross* (1898–1900), led by the Norwegian Carsten Borchgrevink, was the first to winter on the continent, at Cape Adare. These two wintering parties involved twenty-nine men from nine nations, all part of the COMNAP nations. COMNAP has its roots in this long-standing, ongoing tradition of international collaboration in the conduct of Antarctic research.

COMNAP was established in 1988. Its primary function and activities are related to the exchange of operational information in order to improve the way National Programs fulfill their various missions, jointly or independently. That includes mutual support in the design, ongoing improvement, and operation of Antarctic facilities and transport infrastructure.

The infrastructure includes year-round and seasonal stations, ships, airfields, and aircraft. In 2005, COMNAP members operated thirty-seven year-round stations and twelve significant seasonal stations in Antarctic Treaty territory. The combined average of these stations was 1030 for the winter population and 3760 for the peak summer population. COMNAP nations also operated thirty-nine vessels of between 1400 and 40,000 tons displacement in the Antarctic Treaty area.

COMNAP includes a permanent Standing Committee on Antarctic Logistics and Operations (SCALOP) and a number of other groups focused on various areas of expertise. The bulk of COMNAP's work is achieved through these technical groups. Their continual exchange of information provides a vehicle for addressing a wide range or issues, sometimes highly technical, to identify practical solutions in the support of National Antarctic Programs.

A COMNAP Executive Committee (EXCOM) is responsible for all matters between full meetings of the council. A secretariat provides a central point of contact; operates communications and support infrastructure, runs a central information repository; and maintains coordination between members.

In addition to supporting its members, COMNAP works with the other Antarctic organisations to support effective, sustainable Antarctic expeditions and the success of the Antarctic Treaty System.

BEAU RIFFENBURGH

See also **Antarctic Treaty System; Argentina: Antarctic Program; Australia: Antarctic Program; Belgian Antarctic *(Belgica)* Expedition (1897–1899); Belgium: Antarctic Program; Borchgrevink, Carsten E.; Brazil: Antarctic Program; British Antarctic *(Southern Cross)* Expedition (1898–1900); Bulgaria: Antarctic Program; Canada: Antarctic Program; Chile: Antarctic Program; China: Antarctic Program; de Gerlache de Gomery, Baron Adrien; Finland: Antarctic Program; France: Antarctic Program; Germany: Antarctic Program; India: Antarctic Program; Italy: Antarctic Program; Japan: Antarctic Program; National Antarctic Research Programs; Netherlands: Antarctic Program; New Zealand: Antarctic Program; Norway: Antarctic Program; Poland: Antarctic Program; Russia: Antarctic Program; South Africa: Antarctic Program; South Korea: Antarctic Program; Spain: Antarctic Program; Ukraine: Antarctic Program; United Kingdom: Antarctic Program; United States: Antarctic Program; Scientific Committee on Antarctic Research (SCAR)**

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CRABEATER SEAL

The crabeater seal *(Lobodon carcinophaga)* has a circumpolar Antarctic distribution. The vast majority of crabeater seals spend their entire lives in the shifting pack ice surrounding the Antarctic continent, hauling out regularly on ice floes to rest, breed, and moult, and foraging in the surrounding ocean. Some crabeater seals have been found on the southern fringes of South Africa, Australia, New Zealand, and South America, but such vagrants are very rare. Crabeater seals are also occasionally found on fast ice close to the Antarctic continent, and some carcasses of crabeater seals have even been found on the Antarctic continent up to 100 km from open water.

The crabeater seal is by far the most frequently sighted seal species in the pack ice region. Crabeater seals can be distinguished from other species by their slender body form and pointed, slightly upturned snout. The pelt is usually medium-brown to silver over most of the body, although darker colouration and spotting are not uncommon on the front and rear flippers and flanks. Because the hair fades in colour throughout the year, recently moulted seals may be darker than those about to begin their moult, whose pelts can appear silvery white. Crabeater seals can be highly mobile on ice, using their front flippers to assist them and moving the hind flippers in a sinuous, sideways motion. Adults may reach maximum weights of up to 410 kg and lengths of 260 cm, but a typical size range during the summer moulting period would be 180–225 kg weight and 205–240 cm length. Females are usually slightly heavier and longer than males. Crabeater seals may live for up to 40 years, but a life span of 20–25 years is more typical.

Crabeater seals are known to move seasonally in northward and southward directions with the seasonal expansion and contraction of the pack ice, and some individuals have been observed to move substantial distances in east-west directions around the continent. Although crabeater seals can occur anywhere in the pack ice, they have been observed at highest densities in the frontal zones associated with the shelf break and the ice edge. Upwellings, currents, and eddies at the shelf break are thought to result in high concentrations of Antarctic krill, the crabeater seal's preferred prey.

The crabeater seal is very abundant in the pack ice, and it is often claimed to be the most abundant seal species in the world. However, estimating abundance of this and other seal species in the remote and inaccessible pack ice is extremely difficult. Existing estimates of crabeater seal abundance vary widely (2–75 million) and can only be considered approximate. Estimates in the range of 10–15 million are currently considered to be the most realistic, but these are based on surveys undertaken over two decades ago. A recent international research effort in the late 1990s aimed to improve knowledge of the status of this species at both regional and circumpolar scales. Genetic studies suggest there are no subspecies and the circumpolar population is panmictic.

Except when breeding and moulting, crabeater seals generally haul out daily throughout the year to rest on ice floes. During the summer period most individuals begin to haul out in the early morning and cease hauling out late in the afternoon, with the population reaching a peak around midday. At the midday peak in summer about 80% of individuals are generally on the ice, with the other 20% remaining in the water. This pattern appears to change seasonally, with one study finding less than 40% of seals hauled out at the peak time in the months March to May, and more seals hauling out at midnight than at midday in April and May. When breeding, crabeater seals haul out on the ice continuously for extended periods of up to three weeks, thereby undergoing an enforced fast.

Periods of diving and foraging typically occur at night during the summer period, but at other times of the year diving and foraging activity has been observed more frequently during the day than at night. Such daily foraging periods may extend for up to 16 hours, and in one instance an individual has been recorded diving repeatedly without a rest for 44 hours. Most dives by crabeater seals are relatively shallow (<40 m) and short (<5 minutes), but occasionally individuals dive to depths of 300–500 m. Dives during the crepuscular periods are often deeper than dives during the night. It has been suggested that deep dives of several hundred metres may be undertaken to listen for other seals, hear navigation cues or locate new krill swarms, rather than to catch prey.

The pupping season occurs from late September through to early November. At this time, pregnant females haul out on the ice to give birth to a pup, and are joined by a male just before or after parturition. Pups weigh 20–35 kg at birth. Lactation lasts approximately three weeks, during which time the pups gain about 60–80 kg in weight. Once they have located a female, males remain with her throughout the lactation period and defend her from other approaching males. Females may react aggressively to the close approach of any male until ready to mate. Small wounds around the head and neck on both sexes are likely to be due to aggressive intraspecific encounters during the breeding season. Mating has never been observed, but is generally considered to occur after weaning, which may be initiated by the male forcing the female away from the pup to form a male-female pair. When the male and female cease extended haulout and enter the water, they appear to remain close together for only a few days at the most, suggesting that the male-female bond does not last beyond a single season. Some males have been observed to haul out for more than one extended period during the breeding season, indicating that they may try to mate with more than one female. After reaching sexual maturity, female crabeater seals mate and pup during most years. One study estimated the pregnancy rate of sexually mature females at 0.87. The gestation period is 8.5 months.

Very little is known about crabeater seals between the time they are weaned and the time they enter the breeding population at age 2.5–4.5 years. It is thought that mortality in the first year may be as high as 80% due to predation by leopard seals. A high proportion of adult crabeater seals have large, raking scars on their lower flanks, which by their size, form and shape are thought to have been inflicted by leopard seals during unsuccessful attacks.

Apart from predation by leopard seals, little is known about other causes of mortality. Killer whales have been observed hunting crabeater seals and suggested as an additional predator of all age classes, but there is no information on the importance of such predation. An incident of mass mortality involving several hundred crabeater seals near the Antarctic Peninsula in 1955 was speculated to have been caused by a distemperlike virus specific to crabeater seals. Weddell seals in the same area did not appear to be affected. Later studies of crabeater seals along the Antarctic Peninsula confirmed the presence of antibodies similar to those related to canine distemper and phocine distemper, which were responsible for major epizootic die-offs of harbour seals in the Northern Hemisphere in the late 1980s.

Outside of the breeding season, crabeater seals are usually solitary or occur in small groups, but large aggregations have occasionally been observed. The reason for such aggregations remains speculative. Contraction of the ice in summer may force seals to aggregate on the remaining isolated floes, particularly in January and February when they moult, in which case there may be no behavioural or ecological benefit associated with aggregation. On the other hand, aggregations have been observed in the water with apparent coordinated diving behaviour, suggesting a possible benefit of improved feeding efficiency.

Contrary to its name, the crabeater seal feeds primarily on krill. Most investigators have reported krill comprising over 95% of the diet, with fish and squid being minor dietary items. The species does not appear to switch prey seasonally in response to varying availability as does the leopard seal. Crabeater seals have finely divided, lobed teeth that are thought to be an adaptation to their specialised diet of krill. The multiple cusps of the upper and lower postcanine teeth closely interlock to form a sieve that can be used to filter krill from seawater. A bony protrusion on the lower jaw behind the most posterior postcanine teeth fills a gap in this sieve so that krill cannot escape at the rear of the mouth. Given the abundance of crabeater seals, their size, and the dominance of krill in their diet, the crabeater seal is likely to consume more krill in the Southern Ocean than any other single species.

Krill predators, including the crabeater seal, are considered useful as indicators for management of the Southern Ocean ecosystem, particularly in relation to the harvesting of krill. The Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) aims to manage the harvesting of krill in a sustainable manner. The crabeater seal was selected as an indicator species for the CCAMLR Ecosystem Monitoring Program, which aims to detect any effect of krill harvesting on the krill-based ecosystem. The age at sexual maturity of crabeater seals is one population parameter thought to be responsive to changes in krill availability. Age at sexual maturity for crabeater seals fell from 4.5 years in the 1940s to 2.5 years in the late 1960s, then increased again to approximately 4 years in the 1970s. These variations have been interpreted as a response to changes in krill availability and competition between krill predators across a period when harvesting of krill-consuming whales was reduced.

Crabeater seals have been harvested for commercial purposes sporadically in the past: in 1964–1965 by Norway, and in 1986–1987 by the former Soviet Union. While both harvesting ventures proved to be economically unsuccessful, concern over possible future exploitation of this and other Antarctic seal species resulted in the establishment of the Convention on the Conservation of Antarctic Seals, which came into effect in 1978.

Colin Southwell

See also **Leopard Seal; Pack Ice and Fast Ice; Ross Seal; Sealing, History of; Seals: Overview; Weddell Seal; Zooplankton and Krill**

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CRESTED PENGUINS

Penguins in the genus *Eudyptes* are referred to as crested penguins. They are small to medium penguins, blue-black on their backs and white ventrally, that in adult plumage have plumes of yellow or orange feathers above their eyes and red bills. Immature birds are duller in their colour. They are capable swimmers and agile on land.

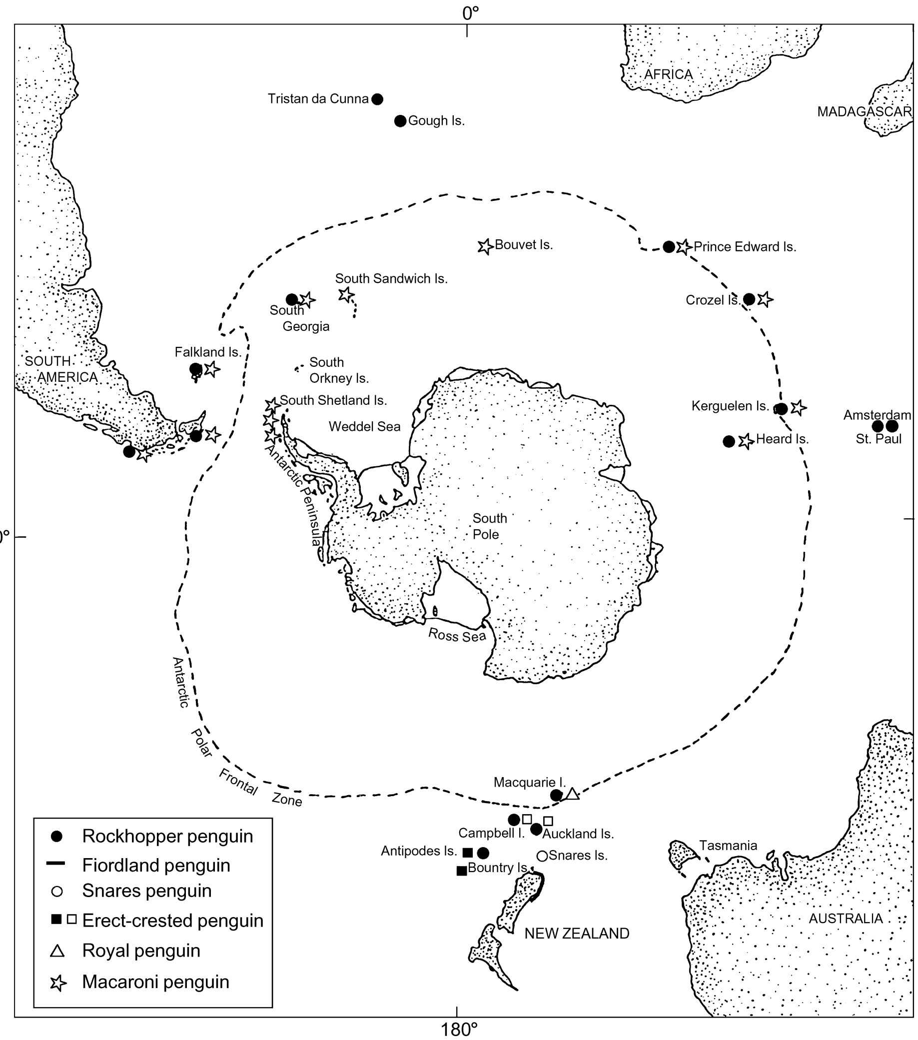
Six species of crested penguin are usually recognized: rockhopper penguin *E. chrysocome,* Fiordland penguin *E. pachyrhynchus,* Snares penguin *E. robustus,* erect-crested penguin *E. sclateri,* royal penguin *E. schlegeli,* and macaroni penguin *E. chrysolophus*. However, the systematics of the genus have not been straightforward. Both the Snares and erect-crested penguins have been treated as races of the Fiordland penguin, although there are morphological grounds to differentiate between them, breeding seasons are dissimilar and hybridization has not been recorded. The rockhopper penguin is divided into three subspecies, one of which, *moseleyi,* has been considered by some sufficiently different to qualify as a separate species. The royal penguin, which is found only on Macquarie Island, was previously treated as a subspecies of the macaroni penguin, which occurs in the southwest Indian and South Atlantic oceans. The two species are similar, except for the amount of blue-black feathering on their cheeks and throat. Whereas these feathers are dark in macaroni penguins, they are white or pale grey and highly variable in royal penguins. There are also differences in measurements between these two penguins. However, penguins with white faces and throats have been found in colonies of macaroni penguins at several islands. The traditional treatment of six *Eudyptes* species has been followed here. The macaroni penguin is treated in greater detail in a separate entry.

The Snares (2.5–2.6 kg) and rockhopper (2.9–3.1 kg) penguins are the smallest of the crested penguins. The macaroni and royal (both 5–6 kg) and erect-crested (5.4–6.4 kg) penguins are considerably larger. Of intermediate size is the Fiordland penguin (4.0–4.5 kg). Males are typically larger and heavier than females.

Distribution

The crested penguins are found in the cool temperate, sub-Antarctic and Antarctic regions of the Southern Hemisphere. The rockhopper penguin has a circumpolar distribution. The northern race, *E. c. moseleyi,* has the most northerly distribution of any crested penguin, breeding at Tristan da Cunha and Gough islands in the Atlantic Ocean and at Île Amsterdam and Île St. Paul in the Indian Ocean. The southern race, *E. c. chrysocome,* breeds around Cape Horn in southern Chile and Argentina, at the Falkland Islands and occasionally at South Georgia. The eastern race, *E. c. filholi,* breeds in two well-separated regions: on the Prince Edward Islands, Îles Crozet, Îles Kerguelen, and Heard Island in the south Indian Ocean and at Macquarie Island, the Auckland Islands, the Campbell Islands, and the Antipodes Islands to the south and east of New Zealand.

Four crested penguins breed only in the southwestern Pacific Ocean. The Fiordland penguin breeds along the south and southwest coasts of New Zealand's South Island, including several islands off these coasts. The Snares penguin is endemic to the Snares



The breeding distributions of crested penguins.

Islands, south of New Zealand. The erect-crested penguin breeds in high numbers at the Antipodes and Bounty groups of islands, to the southeast of New Zealand. Farther south, it previously bred in low numbers at Auckland Islands and at Campbell Island. Still farther south, the royal penguin breeds only at Macquarie Island and adjacent islets.

The breeding distributions of the different crested penguins generally do not overlap. Overlaps exist: Southern rockhopper penguins occur with macaroni penguins around Cape Horn, at the Falkland Islands and at South Georgia, and eastern rockhopper penguins occur with macaroni penguins in the south Indian Ocean, with royal penguins at Macquarie Island and formerly with low numbers of erect-crested penguins at the Auckland and the Campbell islands.

Crested penguins are thought to migrate away from their breeding localities in the nonbreeding season. However, their nonbreeding distributions are often poorly known. Southern rockhopper penguins at Falkland Islands move to the north, west, and south when not breeding, utilizing a number of areas including the slope of the Patagonian Shelf and coastal areas off South America. Vagrant crested penguins are often recorded far from their breeding colonies. For example, rockhopper, Fiordland, Snares, erect-crested, and royal penguins all have been recorded along southern Australia.

Annual Cycle

Crested penguins moult once each year, when they replace all their feathers. During this time, they are ashore for 3–8 weeks, the period varying between species and breeding localities, and cannot feed as they cannot enter the water. They often moult at nest sites but Fiordland penguins do not usually do so. Before moulting, crested penguins leave to sea for average periods of 13–70 days (depending on the species) to fatten up. Once the moult is complete, they go back to sea to regain condition. They return to their colonies to breed for the following season.

Fiordland penguins start to arrive at colonies to breed from mid-June, Snares penguins from mid-August, erect-crested penguins from early September, royal penguins from mid-September, and rockhopper penguins, which generally breed later at higher latitudes, in October or early November. Usually males arrive at colonies for breeding several days earlier than the females. After returning for breeding, the parents fast again for periods that differ among species and between the sexes, but average 33–43 days. During this period, courtship occurs and eggs are laid. Soon afterwards males leave to feed and then return to relieve their partners, the early incubation shifts of the two parents lasting 10–14 days on average.

The females are back at their nests shortly before the eggs hatch. Both parents attend the nest for a few days following hatching, after which the female goes to sea to provision the chick leaving the male to guard it. In rockhopper penguins, the guard stage may last 26 days and the male may fast at this time for 36 days. When chicks are about 3 weeks old, they start to form crèches. The males then leave to sea to feed. Once they have regained condition, they assist the females in feeding the chick. In crested penguins, the incubation period averages between 33 and 36 days, and the fledging period between 60 and 75 days.

Breeding birds depart on their premoult feeding trip soon after their chicks have left the colony. There is often considerable synchrony in the timing of moult, arrival at colonies for breeding and subsequent departure, so that during premoult and postmoult feeding trips colonies are mostly devoid of birds.

Breeding and Survival

Crested penguins typically nest in colonies, some species being more densely packed than others. Rockhopper penguins often breed on rocky terrain, including shores, lava flows, cliffs, and overhangs. Fiordland penguins use dense, temperate rain forest in addition to caves, rock falls, and rock overhangs along coasts. Snares penguins breed on flat, muddy areas or on gentle rock slopes. Nests are under the shelter of forest or scrub, or in swampy areas, among rock falls or on exposed granite. Erect-crested penguins use rocky terrain, often without substantial soil or vegetation. Royal penguins breed on beaches, scree slopes, or hills, on sandy, rocky, or pebbly ground without vegetation.

Most rockhopper and Fiordland penguins breed with the same mate (if alive) in successive seasons, but some may change partners. Snares and erect-crested penguins show strong fidelity both to nest sites and to partners. Bonds of royal penguins are also long lasting.

Nests are often scrapes in the ground that are formed by the female, rotating her body and raking backwards with her feet, and lined with material collected by the male (pebbles, bones, pieces of vegetation).

Crested penguins typically lay clutches of two eggs, which are laid with an interval of 4–5 days. The first (A) egg is on average 17%–44% smaller than the second (B) egg. It usually does not survive, and is discarded by some species after laying of the B egg. Eggs are held by the feet and incubated with a brood patch. Chicks gain mass rapidly after hatching. If both eggs hatch, the chick from the A egg will usually die. Crested penguins do not rear more than one chick to fledging in any year. For Snares penguins, chicks of all ages are able to recognize the calls of their parents.

Most rockhopper penguins breed for the first time when 4–5 years old, Fiordland penguins when 5–6 years old, and Snares penguins when 4–7 years old. Some royal penguins lay eggs when 5 years old but others do not start breeding until aged 11 years. Age at breeding of erect-crested penguins is not recorded. In some seasons, for example when food is scarce, it is likely that not all mature birds breed.

Annual survival of rockhopper penguins is about 39% for birds in their first year and 84% for adults. Fiordland and Snares penguins may live for 10–20 years. For Snares penguins, survival is about 15% in the first year and 57% in the following two years. Annual survival of adult royal penguins is 86% or higher.

Food and Feeding

The food of crested penguins varies among species, breeding localities, and seasons, consisting primarily of crustaceans (especially euphausiids), cephalopods, and fish. Rockhopper penguins eat mainly crustaceans at southerly sites, with fish and cephalopods increasing in the diet that is fed to older chicks at these sites, and predominating at some northern localities. Fiordland penguins feed mostly on small cephalopods or fish. Snares and erect-crested penguins feed mainly on crustaceans and cephalopods.

At Macquarie Island, royal penguins, which feed near the Polar Front while breeding, eat more fish and less crustaceans than rockhopper penguins. Food is caught by pursuit diving. Crested penguins feed solitarily or in small- to medium-sized groups.

Population Sizes

There are very large differences in the estimated sizes of the populations of the different species of crested penguins. Those species having a restricted distribution in New Zealand, or at its islands, are the least abundant. The Fiordland penguin is thought to number 2500–3000 breeding pairs, the Snares penguin 23,250 pairs, the erect-crested penguin 77,000–81,000 pairs, the royal penguin about 850,000 pairs, the rockhopper penguin about 1.5 million pairs, and the macaroni penguin about 9 million pairs. For the subspecies of rockhopper penguins, there are about 600,000 pairs of *chrysocome,* 365,000 pairs of *moseleyi,* and 563,000 pairs of *filholi.*

Conservation Status

On the Red List of IUCN (the World Conservation Union), the erect-crested penguin is listed as Endangered and the other five crested penguins as Vulnerable. The macaroni penguin's status is discussed under the entry for that species.

The erect-crested penguin is regarded as Endangered because its population has decreased by at least 50% in the last 25 years, a time period well within the 45 years considered to span the three most recent generations of this species. In 1972, one pair was breeding at the Auckland Islands and it was thought likely that others were breeding amongst rockhopper penguins. There was a small population of twenty to thirty pairs at the Campbell Islands in 1986–1987, but there have been no recent records of breeding at this locality. The population is now confined to the Antipodes and Bounty groups of islands. At Antipodes Islands, the population decreased by about 50% between 1978 and 1995, when there were 49,000–57,000 breeding pairs, and there have been further decreases since. Different census methods estimated the population at Bounty Islands to be 115,000 pairs in 1978 and 28,000 pairs in 1997–1998.

The Fiordland penguin qualifies as Vulnerable because it has a small population that, based on monitoring at a few sites, is assumed to be undergoing a rapid long-term reduction. The Snares and royal penguins have been classified as Vulnerable because they are restricted either to a small group of islands or to a single breeding location and subject to a number of threats. Populations of both species are thought to be stable, although there is little information for Snares penguin and no recent data on the population size of royal penguins since the early 1980s.

The rockhopper penguin is regarded as Vulnerable because many populations have undergone massive decreases. At the Falkland Islands, southern rockhopper penguins decreased by more than 80% from 1.5 million pairs in 1932–1933 to 264,000 pairs in 1995–1996, at a rate of about 2.75% per annum. In 2000–2001, the population was about 273,000 pairs, suggesting recent stability in the population trend. At Straten Island in Argentina, numbers are also thought to be stable. At Amsterdam Island, the breeding population of the northern race decreased at a rate of 2.7% per year between 1971 and 1993. At the Campbell Islands, the breeding population of the eastern race decreased by 94% between the early 1940s and 1985. The breeding populations at Auckland and Antipodes Islands also have decreased. At Marion Island, the population decreased from 173,000 pairs in 1994 to 67,000 pairs in 2001. Some decreases may have resulted from an altered availability of food caused by increased sea temperatures. In 1985–1986, a mass mortality of rockhopper penguins at the Falkland Islands was thought to be linked to starvation before moult. The arrival mass of adult rockhopper penguins at Marion Island has decreased steadily since 1994–1995, suggesting a decreased availability of food there. An increase in numbers of sub-Antarctic fur seals *Arctocephalus tropicalis* may have influenced the decrease in numbers of rockhopper penguins at Île Amsterdam.

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See also **Amsterdam Island (Île Amsterdam); Antarctic Important Bird Areas; Auckland Islands; Campbell Islands; Crozet Islands (Îles Crozet); Fish: Overview; Heard Island and McDonald Islands; Kerguelen Islands (Îles Kerguelen); Macaroni Penguin; Macquarie Island; Penguins: Overview; Polar Front; Prince Edward Islands; South Georgia; St. Paul Island (Île St. Paul)**

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CROZET ISLANDS (ÎLES CROZET)

Îles Crozet is an isolated archipelago lying in the Southern Indian Ocean (45°68′ to 46°26′ S, 50°14′ to 52°15′ E), some 2400 km southeast from South Africa and 2400 km north of the coast of Antarctica. The archipelago consists of five main oceanic and volcanic islands in two groups. The western group consists of three parts. Île aux Cochons (46°05′ S, 50°15′ E) is a volcanic cone, 9 km in diameter, 770 m high, with an area of about 70 km^2, and with steep western slopes. It is the least eroded of the group, probably the last to erupt. Île des Pingouins (46°27′ S, 50°22′ E) is 53 km to the south of Île aux Cochons. With 4.6 km^2 and a height of 340 m, it consists of a young volcano, about 1 million years old, the main part of which has sunk down into the sea. Ilôts des Apôtres comprises two islands and 12 rocks. The principal island (45°58′ S, 50°25′ E), named Grande Terre, is 3 km long, 2 km^2 in area, and 289 m high, with steep western cliffs.

The eastern group (which lies about 100 km to the east) consists of two islands. Île de la Possession (46°25′ S, 51°45′ E) is the largest island in the archipelago (146 km^2). It is roughly rectangular in shape, 30 km by 15 km. The topography is dominated by an inland chain of mountains, up to 934 m (Pic du Mascarin), with deep glacial valleys to the north and east, and high cliffs to the west and south. Île de l'Est (46°25′ S, 52°15′ E), 20 km east of Île de la Possession, is oval, 18 km by 10 km, with an area of 130 km^2. It has numerous peaks, with deep valleys, the highest point being 1090 m (Pic Marion). Most of the coastline is bordered by high cliffs.

Mostly magmatic, the eastern group of islands present volcanic and plutonic rocks, whereas the western group is only volcanic, with sedimentary levels.

These islands lie north of the Polar Front. The climate is oceanic and cold: the mean air temperature is 5.1°C, with a weak seasonal thermal range (monthly mean temperatures range between 3.0°C in winter and 7.9°C in summer). There is high rainfall (2400 mm per year) and strong winds. There are no glaciers, but there is evidence of past glaciations, as suggested by large glacial valleys on Île de l'Est and Île de la Possession.

On the coasts, the herbs *Crassula moschata* and *Leptinella plumosa* are common. Tussock grassland of *Poa cookii* dominates in the coastal areas influenced by elephant seals or penguins. At higher altitude and up to about 150 m asl, dwarf shrub (*Acaena magellanica*) and fern (*Blechnum penna-marina*) are dominant, with the Kerguelen cabbage *Pringlea antiscorbutica* in the moist places. In the inland valleys, numerous mosses, liverworts, and the grass *Agrostis magellanica* grow on peaty soil. Above 150 m, fellfield vegetation predominates, comprising the cushion herb *Azorella selago* with *A. magellanica*. The vegetation cover is very low in these areas. Twenty-four autochtonous vascular plant species have been recorded at Île de la Possession. There is no endemic species to the archipelago, but most of the flora belongs to the Southern Indian Ocean biogeographical province. Alien plants are mainly localised in the vicinity of the base station on Île de la Possession. Among the fifty-nine species recorded in 1996, few of them colonise the island: *Poa annua* and *Cerastium fontanum* are the most widespread. *Rumex acetosella* and *Poa pratensis* grow near the old sealers camp at Baie Américaine. *Sagina procumbens* is currently in a rapid spreading stage, developing along tracks and near the field huts. Few alien species have been recorded on the other islands of the archipelago, and Île des Pingouins is entirely free of introduced species.

The islands host more breeding seabird species than any other island group in the world. Thirty-six species of bird breed in the group (eighteen on Île aux Cochons, twenty-four on Île de la Possession, thirty on Île de l'Est), with the total number of birds estimated at 25 million. Among the most common birds are king penguin (world's largest colonies), macaroni penguin, rockhopper penguin, wandering albatross, sooty albatross, light-mantled sooty albatross, northern giant petrel, southern giant petrel, several other petrel species *(Pachyptila salvini, Pterodroma brevirostris, Procellaria aequinoctialis, Pelecanoides georgicus),* Subantarctic skua, kelp gull, Crozet shag *(Phalacrocorax albiventer melanogenis),* Antarctic tern, Kerguelen tern, Kerguelen pintail *(Anas eatoni),* and the endemic Crozet lesser sheathbill *(Chionis minor crozettensis)*. Several species are very abundant on the small off-lying islands, but not on the main islands. Île des Pingouins, for example, hosts large numbers of yellow-nosed albatross, blue petrel *(Halobaena caerulea),* and fairy prion *(Pachyptila turtur)*.

Southern elephant seals are abundant. Antarctic furs seals and sub-Antarctic fur seals, previously hunted to the verge of extinction, are rapidly recovering.

Introduced mammals occur on several islands: black rats on Île de la Possession, rabbit on Île de l'Est and Île des Cochons, and cats and domestic mice on Île des Cochons. Their impact on the native communities is not well documented, but the presence of rats on Île de la Possession seems responsible for the rarefaction of some petrel species that remain abundant in similar habitats of Île de l'Est. In addition, salmonid fishes have been introduced in two rivers of Île de la Possession *(Salmo trutta* and *Salvelinus fontinalis)*.

The rate of endemism is exceptionally high in the invertebrate fauna: 57% of the sixty-three insect species recorded on Île de la Possession are known only in Îles Crozet. Among the thirty-five weevils recorded, twenty-six are endemic. There are few introduced invertebrates, and those are mainly present at the research station on Île de la Possession: for example, earthworms *(Dendrodrilus rubidus tenuis)* and aphids in glasshouses *(Myzus ascalonicus)*.

The Islands were discovered on January 22, 1772, by a French expedition headed by Marion Dufresne whose first mate, Julien Crozet, made the official claim two days later. The islands were visited sporadically by sealers in the nineteenth century. Several shipwrecks occurred.

A scientific and meteorological station was established on Île de la Possession in 1962: the Alfred-Faure station hosts about thirty-five people in summer, and twenty people in winter. The main scientific activities are related to geophysical observations and biology. There is no economic activity (fishing or tourism).

Yves Frenot

See also **Antarctic Fur Seal; Antarctic Tern; Conservation; Crested Penguins; Fish: Overview; France: Antarctic Program; France: Institut Polaire Français Paul-Emile Victor (IPEV) and Terres Australes et Antartiques Françaises (TAAF); Kelp Gull; Kerguelen Islands (Îles Kerguelen); Kerguelen Tern; King Penguin; Light-Mantled Sooty Albatross; Liverworts; Macaroni Penguin; Mosses; Northern Giant Petrel; Petrels (Pterodroma and Procellaria); Polar Front; Sooty Albatross; Southern Giant Petrel; Sub-Antarctic Fur Seal; Sub-Antarctic Skua; Wandering Albatross; Yellow-Nosed Albatross**

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CRYOCONITE COMMUNITIES

Cryoconite holes form as windblown particulates accumulate on the surface of a glacier, are warmed by the sun, and melt into the ice producing a cylindrical basin of liquid water. Organisms released from the melted glacial ice and attached to deposited airborne particulates provide the biological inoculum for these ecosystems. This environment lacks a significant source of allochthonous nutrient input and relies on photosynthesis and nitrogen fixation carried out by the resident algae and cyanobacterial species, which provide carbon and nitrogen resources which can be assimilated by the community. Cryoconite holes occur globally in glaciated environments of the Arctic and Antarctic, and are also present in alpine glaciers.

Unlike the open holes found in temperate latitudes, cryoconite holes in the McMurdo Dry Valleys of Antarctica are sealed with an ice lid (up to 30 cm thick) and are frozen solid for the majority of the year. During the austral summer (November–March), the 24 daylight hours and increased temperature enable liquid water to exist, as heat-absorbing sediments in the bottom of a mature cryoconite hole are warmed by solar irradiation, melting a portion of the overlying ice. The austral summer is also a time when new cryoconite holes form, and this process is greatly accelerated by the presence of cracks and depressions within the glacial ice surface, which serve to collect and concentrate sediment. During the few months in which liquid water is present, photosynthetic primary production is possible and these aquatic ecosystems become metabolically active, but are then destined to refreeze and become dormant through the cold, dark winter months.

Bacterial species (including cyanobacteria) in cryoconite hole environments are similar to those found in ecosystems within the permanent ice cover of lakes and in microbial mats (layered groups or communities of microbial populations) of this dry valley ecosystem. This implies that the species within cryoconite holes originate from adjacent terrestrial sources and suggests that similar survival strategies may be in effect in both lake ice and cryoconite holes. Besides the dry valleys of Antarctica, no other ecosystems are known in which nematodes (unsegmented worms), rotifers (multicellular organisms with a wheellike organ), and tardigrades ("water bears"; small, segmented animals) represent the highest trophic levels in the food web. Although it is still uncertain if these metazoans are active in Antarctic cryoconite holes, there is evidence that they are preserved in these environments. Some nematode, tardigrade, and rotifer species can enter a dormant resting state in which they are resistant to desiccation and freezing, and then commence metabolism when conditions for growth are favorable.

In addition to the inherent interest of Antarctic cryoconite holes as discrete and unique ecosystems, these environments could function as a biological refuge, serving in reverse to reseed surrounding environments in the summer during glacial melting. Cryoconite hole ecosystems exist and thrive under the harsh conditions associated with an Antarctic desert, and therefore provide a terrestrial analog for plausible past or present environments for life in ice on Mars, and may have been an important haven for life during past ice ages.

BRENT C. CHRISTNER

See also **Desiccation Tolerance; Dry Valleys; Exobiology; Microbiology; Nematodes; Rotifers; Sea Ice: Microbial Communities and Primary Production; Tardigrades**

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CRYOSAT

Six and a half years after the program was initiated, CryoSat was launched on 8 October 2005. Unfortunately, it failed to reach orbit due to a problem with the launch vehicle.

CryoSat was the first in a series of Earth Explorer satellites prepared as part of the European Space Agency's (ESA) Living Planet Programme. Approved in 1999, CryoSat was developed as an *Opportunity* mission, the purpose of which was to provide rapid answers to important scientific questions about a specific aspect of the Earth's environment. Its main goal was to determine the variability and trends in the thickness of the Arctic marine ice cover and of ice sheets in the Arctic and Antarctic. To accomplish this goal, CryoSat was to measure ice surface elevation from a 720 km altitude polar orbit (circling to 2° latitude off each Pole) over a nominal three-year mission lifetime. Resulting data would have been used to calculate rates of change in thickness and mass of the polar ice cover in response to climate variations and to validate predictions of diminishing polar ice due to global warming.

The CryoSat satellite carried a primary instrument known as the SAR/interferometric radar altimeter (SIRAL), which was complemented by three other instrument packages for precise orbit determination and accurate attitude knowledge. SIRAL is a microwave radar altimeter operating at a frequency of 13.6 GHz. Altimeters transmit pulses of electromagnetic energy that are reflected or scattered back from the surface. The precisely timed delay between each pair of transmitted pulse and received echo is used to calculate the ice surface height with respect to the known orbital position and orientation of the satellite.

SIRAL is capable of operating in three different modes selected autonomously using commands triggered from knowledge of the satellite ground track position over specific target areas. Over regions of sea ice, SIRAL operates in Synthetic Aperture Radar (SAR) mode, making measurements at 250-metre intervals along the ground track (10 times better than its predecessors). Over steeply sloping or variable ice-sheet terrain, SIRAL operates in SAR interferometric (SARIn) mode using two antennas, which provides greater agility and improved ranging accuracy. Over the level ice-sheet plateaux and global oceans, the default Low Resolution Mode (LRM) acquires data comparable with previous radar altimetry. CryoSat was designed to measure average changes in surface elevation to 1.6, 3.3, and 0.17 cm/year accuracy over sea-ice areas (100,000 km^2), ice-sheet drainage basins (10,000 km^2), and on a continental scale (14,000,000 km^2) for ice-sheet interior regions, respectively.

MARK R. DRINKWATER

See also **Antarctic Ice Sheet: Definitions and Description; Antarctic Peninsula, Glaciology of; Filchner-Ronne Ice Shelf; Glaciers and Ice Streams; ICESat; Ice Sheet Mass Balance; Ice Shelves; Lake Ellsworth; Lake Vostok; Lambert Glacier/Amery Ice Shelf; Larsen Ice Shelf; Marginal Ice Zone; Pack Ice and Fast Ice; RADARSAT Antarctic Mapping Project; Remote Sensing; Ross Ice Shelf; Sub-Glacial Lakes; Thwaites and Pine Island Glacier Basins**

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CRYPTOENDOLITHIC COMMUNITIES

Cryptoendolithic communities—microorganisms inhabiting the structural cavities of porous rocks—are perhaps the most obvious example of how a biotope can be exploited to avoid climatic extremes. Microbial cryptoendolithic communities were first described in 1976 in the Dry Valleys region of South Victoria Land, Antarctica. Although cryptoendoliths are distributed worldwide, they have been most intensively studied in this region through the efforts of E. Imre Friedmann and his coworkers. The Dry Valleys are one of the largest ice-free regions of the Antarctic continent. The climate of the Dry Valleys is characterized by its extreme cold and dryness. In winter, a period of continuous darkness, temperatures drop to as low as –60°C, and winds of up to 100 km/h sweep through the valleys. During summer, average daily air temperatures range from –35°C to –3°C. Constant summertime sunshine can raise the inner temperature of rocks to above the freezing point, to as high as 10°C more than the outside temperature. Added to the cold, the region is also one of the driest on the planet. Such rapid oscillations in temperature and wet-dry cycles create an extremely hostile living environment, described by some as a potential analogue for the conditions on early Mars.

The cryptoendolithic microbial communities of the Dry Valleys are confined to rock types that offer suitable microhabitats with appropriate microclimatic conditions. These conditions are met in the fine-grained sandstones, the dominant substratum of the Dry Valleys, but are also characteristic of coarse-grained quartzite and limestone. Organisms inhabiting rock surfaces and shallow cracks are subject to physical abrasion (from wind-blown sand) and rapid temperature fluctuations. On the contrary, cryptoendolithic microbial communities, even if only a few millimetres below the rock surface, are protected from extreme temperature oscillations because of the thermal buffering of the rocks. Based on the assumption that the lower temperature limit for endolithic metabolism is around –10°C, cryptoendolithic communities can only meet their metabolic needs in less than 1000 hours per annum. An adequate water supply is generally thought to be limiting in endolithic environments, particularly during the short summer period, when the elevated temperatures and presence of sunlight are conducive to photosynthesis. Intermittent snowfall may be the only source of water. Recently a novel endolithic microbial habitat was described in Alexander Island, Antarctic Peninsula. Small cryptoendolithic colonies, composed of cyanobacteria, bacteria and fungi, were found within the translucent gypsum crusts. This microhabitat is proposed to provide protection from desiccation, rapid temperature variation and UV radiation flux while allowing penetration of radiation for utilization by phototrophs.

Cryptoendolithic environments are good examples of absolute extreme environments (i.e., regions where the physical conditions are beyond adaptability). Organisms colonizing rocks are not adapted to their environment; they survive by tolerating it. Thus microorganisms in Antarctic rocks live near the lower limits of their physiological potential, and have no reserves to compensate for changes in the environment should conditions deteriorate. As a consequence, even a minor change in climate can result in local extinctions. In fact, close to 80% of the cryptoendolithic communities of Antarctica are dead or fossilized. The presence of microbial fossils of cryptoendolithic microorganisms in sandstones from Mount Fleming and Taylor Valley (Dry Valleys) was recently demonstrated.

Cryptoendoliths have been the subject of intense investigation, originally by microscopy, chemical, and culture-based methods, and recently through the use of molecular-based tools. Two dominant community types have been identified: lichen-dominated and cyanobacteria-dominated assemblages. Cryptoendolithic lichens are the predominant organisms colonizing the subsurface of sandstone. It appears under the rock crust as a conspicuous zone up to 10 mm deep consisting of distinct parallel colour bands. Typically, a black zone under the crust is followed by white and a green zone. Throughout the colonization zone, the reddish iron oxyhydroxide stain is leached out, and the quartz grains appear colourless. This leaching is caused by oxalic acid, apparently produced by fungi. The black and white zones are formed by filamentous fungi (mycobiont—a term used for the fungal partner of a lichen) and algae (photobiont—the algal partner of a lichen), which together form a cryptoendolithic lichen association. The dark pigmentation of the mycobiont, which in turn, encloses groups of algal cells may be an adaptation to the environment: it absorbs light, thereby increasing the temperature. Below this dark zone, colourless mycobiont filaments form a loose woolly web around the crystals of the rock substrate. The green zone of the lichen-dominated cryptoendolithic community is formed by an association of algae and cyanobacteria. Colourless fungi may also be present in this layer, but they do not form lichen associations with the algae. In some cases the green zone can be absent. A recent comprehensive molecular-based study of both lichen and cyanobacteria dominated communities has shown that these biotopes contain an extensive and varied bacterial population.

The cryptoendolithic growth form is probably the most conspicuous morphological adaptation by lichens to the extreme environmental condition of the Dry Valleys. These cryptoendolithic lichens represent an entirely different type of organization and morphology. In "typical" thallose lichens the mycobiont filaments form a coherent pseudotissue. In cryptoendolithic lichens, in contrast, loose filaments and cell clusters grow between and around the crystals of the rock substrate, and are embedded in the rock matrix. The lichen enters the airspaces of the porous rock for protection against the hostile outside climate.

A further task of Antarctic microbiology will be to test microbial responses under several stressing conditions of aridity, temperature fluctuations, and low temperatures, as well as environmental changes such as increasing UV exposure, to explore how these organisms can outstretch their ability to adapt and also to evaluate their capacity to survive in space conditions. Further investigations of these communities will shed light on their limits of survival, adaptation, resistance mechanisms and on the genes involved. Microbiological research in Antarctica is also relevant in the light of today's discussions on global climate change. Another new line of investigation is the astro/exobiological approach to the search for biosigns (biomarkers and microbial fossils), because we might expect to find similar cryptoendolithic traces of life in Martian rocks.

JACEK WIERZCHOS

See also **Algae; Climate; Dry Valleys; Dry Valleys, Biology of; Fungi; Lichens; Microbiology; Temperature**

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D

DALLMANN, EDUARD

On the basis of Sir James Clark Ross's reports of numerous "black whales," presumed to be southern right whales, during his Antarctic voyages of 1839–1843, the whaling company Deutsche Polarschiffahrtsgesellschaft of Bremerhaven dispatched their vessel *Groenland* to the Antarctic in 1873 on a reconnaissance whaling voyage. She was a bark-rigged vessel of 458 tons with an auxiliary steam engine of 95 hp. In command was Captain Eduard Dallmann. Born on March 11, 1830, in the village of Flethe, now part of Vegesack between Bremen and Bremerhaven, Dallmann had first gone to sea at the age of 15, and from the age of 20 had sailed on whaling vessels from the tropical waters of the Pacific to the Chukchi Sea. He commanded his first ship, a whaler, at the age of 29.

Groenland sailed from Hamburg on July 22, 1873, and it reached King George Island in the South Shetland Islands on November 18. There was no sign of right whales. To compensate for this Dallmann sent his men ashore on Robert, Livingston, Rugged, King George, Elephant, Clarence, and Snow Islands to kill elephant seals and Weddell seals (for their blubber) and fur seals (for their pelts).

Thereafter Dallmann headed south into uncharted waters and coasted along the west coast of what he called Palmer Land (now Brabant Island). Among the features he discovered and named were Cape Groenland, Hamburg Harbour, Bismarck Strait, the Wilhelm Islands, Booth Island, and Petermann Island. Other names he bestowed have been superseded; for example, Roosen Strait is now Neumayer Channel, named by Adrien de Gerlache de Gomery. Dallmann's farthest south was about 66° S. Open water continued farther south, but since there were neither whales nor fur seals he started back north. On January 11, he discovered a deep, sheltered embayment (later named Dallmann Bay).

Rounding the northern tip of Brabant Island into Hughes Bay, Dallmann corrected the positions of several islands, as shown on the Admiralty chart. He also discovered Lüttick (now Liège) Island and Orléans Strait, although he did not name it.

Dallmann then headed east along Bransfield Strait past Astrolabe and Hope islands to the South Orkney Islands, where he took significant numbers of fur seals, Weddell seals, and elephant seals on Coronation Island. On February 6–7, in fog and among icebergs, *Groenland* encountered a violent gale with dangerously high seas; three of her whaleboats were swept away. After watering at Potters Cove on King George Island, Dallmann headed for home. *Groenland* reached Hamburg on July 22, 1874.

In terms of whaling, the voyage was disappointing; not a single southern right whale had been seen, although numerous rorquals (humpback, fin, and blue whales) had been sighted. However, Dallmann had managed to cover the expenses of the voyage by taking more than five hundred pelts of fur seals, as well as the blubber of Weddell and elephant seals, and the blubber and spermaceti of a sperm whale. On the other hand, he had made a significant contribution to the map of the Antarctic Peninsula and its off-lying islands, although several of the names given by Dallmann were later superseded.

William Barr

See also **British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); de Gerlache de Gomery, Baron Adrien; Ross, James Clark; Sealing, History of; South Orkney Islands; South Shetland Islands; Whaling, History of**

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DAVID, T. W. EDGEWORTH

Tannatt William Edgeworth David (1858–1934) was born at the Rectory, St. Fagan's, Wales, the son of the Rev. William David and his wife Margaret (née Thomson), on January 28, 1858. Schooled at home and at Magdalen College School, Oxford, he entered New College, Oxford, in 1876, and graduated BA in 1880, being influenced to study geology by professors Sir Joseph Prestwich and John Ruskin. He began mapping the glacial features around his home, and, thinking to take geology as a profession, enrolled at the Royal School of Mines under J. W. Judd in 1882. He had only a few months at the college, but Judd was impressed with his abilities and recommended him for a position in the Geological Survey of New South Wales, Australia. He began field work in New South Wales soon after he arrived there in November 1882, and was influenced in studying Late Palaeozoic glaciation in Australia by meeting R. D. Oldham, visiting New South Wales in 1885. David's researches in recent, Palaeozoic, and Precambrian glaciation continued through his life (leading to some thirty-eight publications). In 1891, David was appointed professor of geology at the University of Sydney and began to exert influence in both scientific and political circles in Australia, continuing to do so for more than 40 years.

From his childhood days, David had been intrigued by a map in the rectory showing Mount Erebus, but his first direct contact with Antarctic science was in 1895, when he described rocks collected by Carsten E. Borchgrevink (1864–1934) at Cape Adare in 1895. In 1901, he directed his students' attention to Scott's first expedition and the scientific problems that might be answered by Antarctic exploration, and sent written support to Scott.

In mid-1907, David learned of Shackleton's proposed British Antarctic Expedition (1907–1909) and wrote asking to accompany the expedition on the voyage down and returning after the ship had unloaded. He suggested a number of scientific experiments that might be carried out by the then-sole geologist of the expedition, the geology student Raymond Priestley. When Shackleton arrived in Australia, David was influential in raising funds from both government and private sources, had his former student Douglas Mawson appointed as physicist, and for the ship's voyage down and return, students Leo Cotton and W. Hammond. Another Australian, Bertram Armytage, was also in the party. En route, Shackleton persuaded David (who needed little persuasion, although he did not have sanction from the University Senate) to stay for the whole expedition, appointing him chief scientist. David's series of articles written during the short but harrowing trip to Antarctica from Lyttelton, New Zealand, on *Nimrod,* towed for much of the distance by *Koonya,* published in Sydney, were widely circulated, and helped keep the expedition in the news. In later years David's articles and interviews on Antarctic matters supported many Antarctic projects and individuals and often helped separate fact from fantasy.

Although not appreciated by all members of the party (some thought there were too many colonials), David's age (50) and experience helped to maintain the equanimity of the party during the winter months. In March 1908, Shackleton gave David permission to lead an attempt to climb Mount Erebus. Although not particularly difficult in technical terms, this was a first mountaineering challenge for most of the six members of the party (David, Mawson, Alastair Mackay, Jameson Adams, Philip Brocklehurst, and Eric Marshall), with relatively unsuitable equipment and little experience of Antarctic and altitude conditions. The expedition, lasting six and a half days, during which there were a few lucky escapes from injury, reached the active summit—then thought to be above 13,000 feet (13,370 or 4064 m, although now measured as 12,450 feet or 3795 m)—David and Mawson making geological observations en route and at the summit. As Brocklehurst was suffering severe frostbite the party came down quickly, glissading down numerous steep inclines. David provided a long description of the ascent for the volume *Aurora*

Australis, produced at Cape Royds during the winter months. David carried out considerable detailed mapping and collecting in the Cape Royds area.

David took two kites (made in Sydney) to the Antarctic, hoping to use them for meteorological work. These followed the design by the pioneer aeronautic engineer Lawrence Hargrave, who advised how they could be controlled. David was unable to test them before leaving Sydney, and with little or no experience made only one unsuccessful attempt to fly one, being pulled into the air before the kite plunged to Earth with considerable damage.

In early October 1908, David, Mawson, and Mackay set out north from Cape Royds to study the coastal geology and, if possible, to reach the position of the (variable) South Magnetic Pole, as well as exploring the Dry Valleys for minerals, if time allowed. This expedition became one of the legends of Antarctic travel, as it was a man-hauled expedition of some 1260 miles (2030 km), involving a considerable amount of relaying. David's hyperactivity in chasing geological information after periods of heavy hauling, his classical quotations in the midst of pulling, and his physical strength, which was less than that of his colleagues, played upon the nerves of his two younger companions and there were periods of tension between the three, not unusual in such conditions. In the end, they reached only the vicinity of the South Magnetic Pole, their equipment being inadequate for true measurement. Despite this, and the disparity in the physical and mental characters of the three, they made many geological discoveries and succeeded against great natural difficulties. In the next few years David's fundraising in Australia helped in the preparation of the scientific results of the expedition, finally published during the First World War.

David returned to Sydney before the other members of the expedition, which placed him in the centre of attention and invoked numerous articles, cartoons, and events. He was only to be replaced as Australia's Antarctic hero after the tragic events and epic return to base of Mawson in 1912–1913.

David continued to exert considerable influence in Antarctic circles, being responsible for the appointment of all three geologists (Griffith Taylor, Frank Debenham, and Raymond Priestley) to Scott's last expedition (1910–1913). He ensured funding from the Australian Commonwealth and state governments, as well as advising Scott and Edward Wilson on Antarctic conditions. He gave similar help to the Shirase expedition after it arrived in Sydney in dire straits in May 1911, helping it to reorganise before going south again in November 1911.

David was one member of the three-man committee helping organise and gain funding for Mawson's Australasian Antarctic Expedition (1911–1914), and he effectively controlled much of the Australasian end of its affairs. David was supportive of Amundsen when he was being criticised for his assault on the South Pole, and ensured a hearty welcome for him in Australia in March 1912. He was also to the fore when Scott's fate was known, and assisted various members of that expedition when they returned through Sydney.

In 1914, David was instrumental in making *Aurora* available to Shackleton's Imperial Trans-Antarctic Expedition, and he advised later when searches began for the expedition. His interest in Antarctic affairs continued throughout the 1920s, and his help was again invoked in the planning and operation of Mawson's BANZARE of 1928–1930.

Besides his key role in helping Antarctic geologists, many others involved in Antarctic exploration—including Frank Hurley, Frank Wild, Herbert Ponting, Joop Waterschoot van der Gracht, Tryggve Gran, Æneas Mackintosh, and H. T. Ferrar—had David to thank for advice and even financial assistance.

David's charisma, his extraordinary energy, and his organisational abilities ensured that he remained at the forefront of Australian (and indeed international) activities related to the Antarctic until his death in Sydney on August 28, 1934.

David Branagan

See also **Borchgrevink, Carsten E.; British Antarctic *(Southern Cross)* Expedition (1898–1900); British Antarctic *(Nimrod)* Expedition (1907–1909); History of Antarctic Science; Japanese *(Shirase)* Antarctic Expedition (1910–1912); Mawson, Douglas; Priestley, Raymond; Ross Island; Shackleton, Ernest**

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DAVIS, JOHN KING

One of the longest-lived and least-well-known Antarctic explorers of the Heroic Age, John King Davis was born in Surrey, England on February 19, 1884, and died aged 83 in Melbourne, Australia on May 7, 1967. A meticulous navigator and skilled ice pilot, he captained five expedition voyages to Antarctica and served on two more between 1907 and 1930, the highlights of a nautical career that spanned 50 years. From 1920 to 1949 he was Commonwealth Director of Navigation in Australia, his adopted country, and even after his retirement he maintained an interest in Antarctica as a member of the Planning Committee of ANARE (Australian National Antarctic Research Expeditions) until 1962.

All of Davis's Antarctic voyages were made on behalf of expeditions led by Ernest Shackleton (three) or Douglas Mawson (four). Both of those leaders relied totally on Davis's competence, but occasionally felt irked by his caution and his insistence on maintaining the safety of his ship—the paramount responsibility of a professional skipper, whatever might be the desires of the "layman" (as he once called Mawson) expedition leader. For Davis was a seaman, first and last. His initiation came at the age of 16 when he ran away to sea to join the full rigged ship *Celtic Chief* as an apprentice. Her skipper Captain John Jones provided Davis with a role model of "a shipmaster of great integrity and skill, vested with supreme authority over the lives of men, charged with the safety of the ship, her cargo and those who served in her, doomed to that loneliness and austerity inseparable from command" (Davis 1962).

This inspired his entire subsequent career. Within seven years, Davis had gained his first mate's ticket and by March 1907 was back in London on the lookout for a new berth. By chance, a friend took him to visit an exhibition of polar equipment in Regent Street—at the headquarters of Shackleton's British Antarctic Expedition. Learning that the expedition's ship, *Nimrod,* needed a first mate, Davis applied and was eventually signed on. To win a chief's berth so soon after getting his ticket was a very rapid career advance and it was this, as much as his interest in Antarctica, that led Davis to accept the job. But he carried it out so efficiently and enthusiastically that Antarctic exploration shaped his career, and his life, from then on.

After two seasons in the Ross Sea, during which Shackleton and three companions reached 97 geographical miles (180 km) from the South Pole, Davis was rewarded, at the age of 25, with his first command, on *Nimrod*'s return voyage to England. Also on the expedition was a young Australian geologist, Douglas Mawson, a member of the first party to reach the vicinity of the South Magnetic Pole, then in Victoria Land.

With his fierce professionalism, Davis was Mawson's ideal choice for skipper of *Aurora,* the ship of his 1911–1914 Australasian Antarctic Expedition (AAE). Mawson's objectives were to engage in scientific research and chart new territory in the section of Antarctica south of Australia, as well as landing a party on Macquarie Island to set up a radio relay station for the first transmissions from his main base, which was eventually set up at Commonwealth Bay in Adelie Land. After establishing the main base in early 1912, Davis sailed westwards along the unexplored coast to the Shackleton Ice Shelf, where the Western Base party remained under the command of Frank Wild. The next season, after waiting in vain for three weeks at Commonwealth Bay for Mawson to return from an inland expedition, and losing three anchors and almost the ship in the fierce katabatic winds that scoured the anchorage, Davis fought his way west again to pick up the party at the Western Base, as they lacked the resources for another winter. The following year, for yet a third time, Davis negotiated the hazards of the Adelie Land pack to retrieve Mawson and his companions, finally reaching Adelaide in February 1914, "very glad they are all safe in Australia again without mishap" (Davis 1914), an outcome largely due to his skills and commitment.

Davis regarded these three voyages of the AAE as his main life's work, and en route to the ice he also carried out pioneering oceanographic research for which he was awarded the Murchison Medal of the Royal Geographical Society, and which Mawson acknowledged was comparable in scientific value to the research results achieved by the expedition's shore parties.

On his return, Shackleton sought Davis's services as skipper of *Endurance* on the Imperial Trans-Antarctic Expedition (ITAE) of 1914–1917, a post that Davis refused and in so doing escaped being trapped in the ice of the Weddell Sea for 2 years. Instead, he spent the war in the Sea Transport Service, commanding troopships carrying soldiers and horses to the Gallipoli and Western fronts until 1916, when he was drawn back to the ice, as captain of his old ship *Aurora,* to rescue the Ross Sea Party of the ITAE, marooned at Cape Evans.

The final call to Antarctica came in 1929, when Davis was appointed captain of *Discovery,* Robert Falcon Scott's old ship, and second-in-command to Mawson of the British, Australian, New Zealand Antarctic Research Expedition (BANZARE). Although undoubtedly the most experienced Antarctic navigator, Davis was by then 45 and had not held a seagoing command for more than 10 years. From the beginning there were disagreements between Mawson and Davis about the expedition's route, which stemmed from Davis's concern about *Discovery's* limited coal capacity and poor sailing qualities. In addition, Davis believed his extensive experience of oceanographic work in *Aurora* should give him authority over the scientific program. Mawson saw this as his responsibility as expedition leader, and a series of conflicts between the two men led to Davis's resignation from the second BANZARE, of 1930–1931.

There is no doubt that Davis's dour and sometimes irascible personality as ship's captain well deserved his nickname, "Gloomy." But this was as much a reflection of his exceptionally high standard of seamanship, which he demanded also of others, and, although a martinet at sea, his friends found him a delightful companion ashore. Their stormy passage on BANZARE was only a brief interlude that both Davis and Mawson put behind them in resuming their long friendship. Mawson later paid tribute to Davis's skill in navigating the sturdy wooden sailing ships that were the backbone of the Heroic Age of Antarctic exploration, and acknowledged that "beneath a rugged exterior he was a God fearing man, kind, trustworthy and courteous" (Davis 1962).

Davis's skill and professionalism as an Antarctic navigator were recognised by the award of two Polar Medals and two bars, and his work as Commonwealth Director of Navigation with a CBE.

LOUISE CROSSLEY

See also **ANARE/Australian Antarctic Division; Australasian Antarctic Expedition (1911–1914); British Antarctic *(Nimrod)* Expedition (1907–1909); British, Australian, New Zealand Antarctic Research Expeditions (BANZARE) (1929–1931); Geopolitics of the Antarctic; History of Antarctic Science; Imperial Trans-Antarctic Expedition (1914–1917); Mawson, Douglas; Ross Sea Party, Imperial Trans-Antarctic Expedition (1914–1917); Shackleton, Ernest**

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DE GERLACHE DE GOMERY, BARON ADRIEN

Adrien de Gerlache de Gomery was born on August 2, 1866, in Hasselt in Belgium, the son of Colonel Auguste de Gerlache and Emma-Thérèse, née Bicops. At the age of 16 he enrolled at the Ecole Polytechnique of the Free University of Brussels to study engineering. But during the summer vacations he worked as cabin-boy on North Atlantic liners. From January 1886, he served on a variety of ships, and in 1890, he joined the Belgian Navy, whence, in 1893, as a lieutenant, he joined the hydrographic vessel *Le Belgique* as first officer.

Having conceived the idea of mounting a Belgian expedition to the Antarctic, in order to gain practical experience in ice navigation he made a cruise to the Greenland Sea on board a Norwegian whaler. Early in 1895 his plans were approved by the Royal Belgian Geographical Society, and a public subscription was opened. In July 1896, de Gerlache bought the Norwegian whaling ship *Patria,* which he renamed *Belgica*.

Belgica put to sea from Ostend on August 23, 1897, and having called at Punta Arenas on January 14, 1898, headed south. Having passed the South Shetlands, de Gerlache headed into the strait now named after him. Then, pushing farther south, *Belgica* crossed the Antarctic Circle on February 15 and finally, on March 2, 1898, became solidly beset in the ice at 71°30′ S, 85°16′ W.

With numerous twists and turns, the route of its drift thereafter was generally westerly, roughly along the 70° S parallel. The expedition members suffered greatly from scurvy and cold; one man died and at least one became seriously mentally unbalanced. Finally, on March 14, 1899, the ship broke free of the ice. She reached Antwerp on November 5, 1899. This was the first expedition to survive an Antarctic winter.

Soon afterwards, de Gerlache took charge of an expedition aboard the yacht *Selika* to investigate the pearl fisheries of the Persian Gulf, but attempts at pearl fishing were disastrous.

In 1905, *Belgica* was chartered by the Duc d'Orléans and, with de Gerlache in command, made three voyages to the Arctic, in 1905, 1907, and 1909, visiting East Greenland, Svalbard, Novaya Zemlya, and Zemlya Frantsa-Iosifa.

With the outbreak of World War I, de Gerlache was very active. For example, he directed the landing and reembarkation of British troops and guns, and coordinating the evacuation of Belgian refugees to Britain. In October 1914, he took refuge in England, then in Christiana (Oslo), and later Stockholm, where he became a persuasive propagandist for the Belgian cause.

After the war he was closely involved with the reorganization of the Belgian Navy and with officer training. He was made Inspector-General of the Navy in 1926 and Director General of the Navy in 1928.

De Gerlache had married Suzanne-Marie-Jeanne Poulet in Nice on December 21, 1904; they had a son and a daughter. After their divorce in 1913, de Gerlache married Elisabeth Höjer in Stockholm on December 28, 1918; they had one son.

He made Baron Adrien de Gerlache de Gomery on November 19, 1924, he died on December 4, 1934.

William Barr

See also **Belgian Antarctic *(Belgica)* Expedition (1897–1899)**

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DEBENHAM, FRANK

Frank Debenham was born in Bowral, New South Wales, on December 26, 1883. He attended the King's School, Parramatta, and then entered the University of Sydney to read Classics, graduating with a BA in 1906. He later taught at Armidale School, before in 1908 reentering the University of Sydney, where he took a BSc Honours degree in Geology and Petrology. While Debenham was at Sydney the second time, Professor T. W. Edgeworth David returned from Ernest Shackleton's British Antarctic Expedition and began working up the results of the expedition's geological field studies.

In 1910, through the influence of Professor David, Debenham was chosen by Robert Falcon Scott and Edward Wilson to be one of three geologists on Scott's second British Antarctic expedition. Debenham was twice a member of the Western Party, which carried out geological work in the mountains and on the glaciers to the west of the McMurdo Sound. His greatest contribution lay in his expertise in plane-table surveying. The plane-table had never been used before as a regular Antarctic sledging instrument prior to Debenham's doing so. On his first western journey, he made a detailed, large-scale plane-table map of the area traversed, gaining considerable experience not only in general survey methods but particularly in the measurements of glaciers. Meanwhile Debenham also collected a great many geological specimens that were subsequently brought back to the museum of the University of Cambridge's Geography Department.

Debenham was much interested in natural phenomena, and, finding a headless fish on top of the Ross Ice Shelf, he used it to formulate a theory on how the ice shelf was formed. He also became the expedition's official photographer after Herbert Ponting left in 1912. In November 1912, Debenham and fellow geologist Raymond Priestley first raised the idea of establishing a "polar centre."

In 1913, Debenham went with other members of the expedition to Cambridge to work up the many scientific results obtained in the Antarctic. His studies were interrupted by the outbreak of the First World War, and he joined the Oxford and Buckinghamshire Light Infantry, serving in France and Salonika, in the latter of which he was severely wounded. He was demobilized as a major and returned to Cambridge, from where he graduated in 1919.

In 1919, Debenham was appointed to the Royal Geographical Society's lectureship in surveying at Cambridge and he was elected into a fellowship at Gonville and Caius College. He also sent a proposal for the founding of a polar institute to the Captain Scott Memorial Mansion House Fund, which began the process by which Scott Polar Research Institute (SPRI) was founded. Debenham became the first director of SPRI, remaining in the position until 1946. He also was made Reader in the Department of Geography in 1928 and the first professor of that subject at Cambridge in 1931. It was to a great extent because of Debenham's abilities that both SPRI and the Department of Geography became leading world research centers.

Debenham retired from the University of Cambridge in 1949, following which he traveled extensively and continued to publish numerous books and papers. He died in Cambridge on November 23, 1965.

JUNE BACK

See also **British Antarctic *(Nimrod)* Expedition (1907–1909); British Antarctic *(Terra Nova)* Expedition (1910–1913); David, T. W. Edgeworth; Photography, History of in the Antarctic; Priestley, Raymond; Ross Ice Shelf; Scott Polar Research Institute; Scott, Robert Falcon; Shackleton, Ernest; Wilson, Edward**

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DECEPTION ISLAND

Deception Island (62°57′ S, 60°38′ W) is an active volcano in the South Shetland Islands. Its unique landscape comprises barren volcanic slopes, steaming beaches, and ash-layered glaciers. It has a distinctive horseshoe shape with a large flooded caldera. This opens to the sea through a narrow channel at Neptune's Bellows, forming a natural sheltered harbor. It is one of the very few places in the world where vessels can sail directly into the centre of a restless volcano.

The total land area is 98.5 km^2. It is 15 km in diameter and rises to 539 m above sea level at Mount Pond. More than 57% of the island is covered by permanent glaciers. A ring of hills runs around the island and is the principal drainage divide—ephemeral springs flow toward the inner and outer coasts. Several lakes are located on the interior side of the watershed. Kroner Lake is the only geothermal lagoon in the Antarctic.

Approximately 10,000 years ago, a violently explosive eruption evacuated about 30 km^3 of molten rock from Deception Island. The volcano summit collapsed to form the Port Foster caldera. The volcano was particularly active during the eighteenth and nineteenth centuries. Twentieth-century eruptions occurred during two short periods, 1906–1910 and 1967–1970. In 1992, enhanced seismic activity on Deception Island was accompanied by ground deformation and increased water temperatures. Today, the floor of Port Foster is rising rapidly in geological terms, and there are areas of long-term geothermal activity. It is classified as a restless caldera with a significant volcanic risk.

The climate of Deception Island is polar maritime. The mean annual air temperature is –3°C. Extreme temperatures range from +11°C to –28°C. The mean annual equivalent of rainfall is 500 mm. Prevailing winds are from the northeast and west.

Deception Island has a sparse but exceptional flora, including at least eighteen species of moss or lichen that have not been recorded elsewhere in the Antarctic, two of which are endemic. No other area in Antarctica is comparable. Of particular importance are the unique plant communities that grow at the island's geothermal areas, and the largest known community of Antarctic pearlwort *(Colobanthus quitensis)*. Eleven subsites of botanical importance have been proposed as Antarctic Specially Protected Area (ASPA) No. 140.

The benthic habitat of Port Foster is also of ecological interest due to the natural disturbance caused by volcanic activity. Two subsites are currently protected as ASPA No. 145.

Nine species of seabird breed on the island. The world's largest colony of chinstrap penguins is located at Baily Head, on the southwest coast, where an estimated one hundred thousand pairs nest.

The first authenticated sighting of Deception Island was by the British sealers William Smith and Edward Bransfield from the brig *Williams* in January 1820. It was named by the United States sealer Nathaniel Palmer later that year. Also in 1820, Pendulum Cove became the base of the US sealing fleet led by Captain Benjamin Pendleton.

The first scientific expedition to Antarctica, led by the British Captain Henry Foster, visited aboard HMS *Chanticleer* in 1829. Lieutenant Kendall compiled a map of Deception Island, the first accurately surveyed map of an Antarctic landmass.

In 1842, William Smiley of the US sealing vessel *Ohio* gave the first account of a volcanic eruption on Deception Island.

Whaling activities started in 1906–1907. The Norwegian Adolfus Andresen, founder of the Chilean Sociedad Ballenera de Magellanes, used Whalers Bay as an anchorage for whaling factory ships. Between 1908 and 1910, the French explorer Jean-Baptiste Charcot visited to stock up with coal, food, and water and to make repairs to his vessel *Pourquoi Pas?*. In 1912, the Falkland Island Dependencies Government issued a license to Hektor Whaling Company to establish a shore-based whaling station. Approximately 150 people worked at the station during the austral summer, producing more than 140,000 barrels of whale oil. Hektor whaling station was abandoned in April 1931, when whale oil prices slumped.

In 1928, the Australian Hubert Wilkins and the Canadian Carl Ben Eilson undertook the first powered flight in Antarctica, taking off from an improvised ash runway at Whalers Bay. Later, in 1935, Lincoln Ellsworth assembled his aircraft *Polar Star* at Deception Island prior to his pioneering trans-Antarctic flight from Dundee Island. Deception Island was also the base of the Falkland Islands Dependencies Aerial Survey Expedition (1955–1957).

During the 1940s and 1950s, overlapping territorial claims of the Antarctic Peninsula region were upheld by Argentina, Chile, and the UK, and were the source of political tension. Deception Island played a central and important role in the international affairs of Antarctica. In February 1944, the secret British wartime mission Operation Tabarin (the forerunner to the British Antarctic Survey) established its first base (Base B) in the abandoned Hektor whaling station. In 1948, Argentina built Decepción Station at Fumarole Bay. Later, in 1955, Chile built Pedro Aguirre Cerda Station at Pendulum Cove.

Today, Argentina and Spain operate scientific stations on the island during the austral summer. Gabriel de Castilla Station (Spain) is located on the western shore of Port Foster. Science at Deception Island focuses principally upon volcanic monitoring.

The remains of Hektor whaling station, a whalers' cemetery (the largest cemetery in Antarctica), and Base B, partially destroyed by a volcanic eruption in 1969, are now protected as Antarctic Treaty Historic Site and Monument (HSM) Number 71. The remains of Pedro Aguirre Cerda Station, which was destroyed by the 1967 eruption, are listed as HSM No. 76.

Deception Island is the most visited site in Antarctica by tourists. It provides the opportunity for visitors to learn about volcanoes, geothermal activity, and other aspects of the natural world, as well as Antarctic exploration, whaling, and science.

Deception Island was adopted as Antarctic Specially Managed Area (ASMA) No. 4 at Antarctic Treaty Consultative Meeting XXVIII (Stockholm, 2005). The ASMA will incorporate a matrix of ASPAs, HSMs, and visitor sites. This will assure its long-term protection from the competing pressures of science (and the logistical support of science), nature conservation, and tourism.

ROD DOWNIE

See also **Aircraft Runways; Aviation, History of; Bransfield Strait and South Shetland Islands, Geology of; British Antarctic Survey; Charcot, Jean-Baptiste; *Chanticleer* Expedition (1828–1831); Chinstrap Penguin; Ellsworth, Lincoln; Falkland Islands and Dependencies Aerial Survey Expedition (FIDASE) (1955–1957); French Antarctic *(Pourquoi Pas?)* Expedition (1908–1910); Geopolitics of the Antarctic; Heated Ground; History of Antarctic Science; Lichens; Mosses; Palmer, Nathaniel; Protected Areas within the Antarctic Treaty Area; Sealing, History of; South Shetland Islands; South Shetland Islands, Discovery of; Tourism; Vegetation; Volcanic Events; Volcanoes; Whaling, History of; Wilkins, Hubert**

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DECOMPOSITION

Decomposition is the process whereby substances are actively broken down into a number of constituent parts. This might be achieved through biological, chemical, or physical action.

Biological decomposition is primarily mediated by microorganisms. Microbiological decomposers are a key component of the food web and occur at the base of the food chain—in this way, microbial decomposers help to regulate the biogeochemical cycles, including the carbon, nitrogen, and sulphur cycles. They recycle waste materials from living organisms (and indeed the dead organisms themselves), to release bioavailable nutrients; for example, the microbial decomposition of uric acid releases ammonium. Microbial decomposition occurs mainly through bacterial or fungal action, primarily through the excretion of extracellular enzymes, although other types of microorganism are also involved. Often these microorganisms are associated in multispecies groups as consortia or biofilms, thereby enhancing the efficiency of decomposition. Decomposition processes, however, are not restricted to microorganisms—decomposition of food material by digestive enzymes in the gut is also seen in higher organisms.

Chemical reaction can also drive decomposition; for example, consider the chemical decomposition of ozone (O_3) by nitrogen oxide (NO) or chlorofluorocarbons (CFCs) in the atmosphere or the chemical weathering of rock minerals, where minerals in rocks become chemically altered, and subsequently decompose and decay.

Physical processes include the thermal decomposition of minerals, a process particularly associated with volcanic and geothermal activity; shock decomposition through impact, as seen in meteorite impacts; or photolytic decomposition, such as that seen in the chlorofluorocarbons by ultraviolet light.

A variety of experimental methods can be used to quantify rates of decomposition in Antarctic ecosystems. This methodology is based on either direct measurement, for example, in the use of biomarkers and stable isotope analyses to track degradation pathways or indirect measurement, such as the use of cotton strips buried in soil samples to quantify *in situ* rates of decomposition—a method currently in use in the Dry Valley soils. Here, the cotton strips can be recovered after a period of time has elapsed and the level of decomposition determined.

In the Antarctic, decomposition is a relatively slow process, as rates of decomposition are directly affected by both temperature and moisture. Many decomposition processes rely on enzymes and are therefore temperature dependent, while dryness inhibits decomposition. Although the amount of water on the Antarctic continent is high, much of it is unavailable in the solid form, whilst air circulation over the South Pole ensures that the air remains dry. In many Antarctic locations, there is little apparent evidence of decomposition, as relatively small amounts of organic matter exist. In addition, the slow rates of decomposition are demonstrated by the presence of seal and penguin carcasses in the Dry Valleys, some of which have been dated as approximately 3000 years old. As global warming continues, so will these environments warm, suggesting increased rates of decomposition and increased levels of nutrient availability.

A further important consideration, particularly for increasing human activity in Antarctic ecosystems, is that decomposition of waste materials slow. Biodegradation is slow due to low temperatures, so that the removal of pollutants such as oil is difficult.

David A. Pearce

See also **Biogeochemistry, Terrestrial; Carbon Cycle; Dry Valleys; Microbiology; Pollution; Soils**

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DEEP SEA

The deep sea (below 1 km) is by far the largest ecosystem on our planet and yet amongst the least well known. About two thirds of the Earth's surface is covered by the marine environment, of which 90% is deep sea. Despite this, mostly owing to its remoteness, less than a soccer-field-sized area has been studied in sufficient detail to reveal the mostly small organisms inhabiting it.

The absence of sunlight entails a lack of plants and algae, which elsewhere form the foundation of life. So in order to maintain their metabolism deep-sea organisms have to rely on other sources of energy. These stem from inhabitants of the narrow photic zone near the sea surface that eventually fall to the deep sea floor, from tiny single-celled algae and plankton fecal pellets to whole whale carcasses.

Not all life there is dependent on the fall of material from the surface, though. A specialized deep-sea community completely independent of light was discovered in 1974 near submarine hot springs, the so-called hydrothermal vents. In such communities chemosynthetic microorganisms are the primary producers by oxidizing sulphuric compounds. The giant worm *Riftia pachyptila* has reduced its digestive tract and instead relies on symbiotic chemosynthetic bacteria stored in its body that make up half of the worm's weight.

In comparison to other marine habitats, one of the defining characteristics of the deep sea, however, is the scarcity of nutrients, and hence the biomass of animals per recorded area is typically low. Of the larger animals, sea cucumbers and brittle stars are particularly numerous and speciose. Also of note are the giant scavenging *Eurythenes* and *Alicella* amphipods, which grow to more than 14 cm. These are attracted by the odour of bait in spectacularly large numbers. The majority of animal species, however, are significantly smaller than their relatives in shallower water and can only be retained by sieves with meshes of 1 mm (macrofauna) and 0.06 mm or smaller (meiofauna).

The single largest source of the deep-sea water masses is the Southern Ocean around Antarctica, where cold and saline surface waters begin to sink due to high density. The descent of the Antarctic Bottom Water into the deep sea and equivalent waters from the Arctic is part of a global hydrodynamic circulatory pattern (like a conveyor belt) and is the primary reason why the deep sea, except in enclosed basins such as the Mediterranean and the Red Sea, is cold (1°C–4°C) and well oxygenated. This high level of oxygenation is thought to explain why some deep-sea organisms achieve anomalously large size.

This continuity of water masses between the Antarctic shelf and the deep sea is closely mirrored by faunal distribution patterns. While deep-sea fauna are composed rather differently compared to shallow waters at lower latitudes, this distinctness fades at high latitudes. Around Antarctica typical deep-sea taxa are found colonizing shallow waters on the continental shelf (polar emergence) as well as shelf species descending into the deep sea (polar submergence). This faunal exchange is further facilitated by the fact that the continental shelf around Antarctica is at a much greater depth (500 m) than elsewhere (200 m) due to the enormous weight of the ice shield on the continent.

The unexpectedly high biological diversity in the deep sea continues to be debated because it is difficult to understand how so many species could evolve and can coexist today in a habitat that appears rather homogenous. Although records of benthic storms, submarine tides, and debris flows help overcome the idea of physical stability of the environment, the few ecological studies carried out so far have failed to demonstrate the degree of specialization that would traditionally be associated with the coexistence of so many species.

The number of species in the Antarctic deep sea is of importance for answering the question of whether there are indeed fewer species living in polar than in tropic latitudes and if so, what processes might be responsible. This trend is well established for terrestrial habitats but is far less evident or even absent for the marine realm, especially in the Southern Hemisphere.

Although hydrostatic pressure is not *per se* stressful for organisms permanently living in the deep sea, it requires physiological adaptations because the equilibria of biochemical reactions may be shifted, sometimes dramatically, compared with shallower depths when the catalysed reaction involves changes of volume of the reagents.

Experimental deep-sea mining for ferromanganese nodules has been carried out but is in its infancy still. It is currently under investigation whether the disposal of carbon dioxide in deep-sea sediments on an industrial scale can lessen the effect of global warming, but concern about the environmental consequences exists. Disposal of used equipment and waste into the deep sea is a reality, although subject to debate (Brent Spar). To date, the Antarctic part of the deep sea south of 60° S has been environmentally protected since 1959 under the Antarctic Treaty as "...a natural reserve, dedicated to peace and science."

Christoph Held

See also **ANDEEP Programme; Antarctic Bottom Water; Antarctic Treaty System; Biodiversity, Marine; Deep Stone Crabs; Gigantism; Productivity and Biomass**

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DEEP STONE CRABS

Crabs are nearly absent from the Southern Ocean (within the Polar Front), but one group, the stone crabs, are known to occur in several hundred meters of water at South Georgia and along the Antarctic Peninsula. Recently they have also been found at Bouvetøya and at a continental Antarctic site.

The term ''stone crabs'' encompasses several crab-like species pertaining to the family Lithodidae. The best-known representative is the Alaskan red king crab *Paralithodes camtschaticus*. Lithodid crabs are phylogenetically more closely related to hermit, coconut, or mole crabs (such as *Pagurus, Birgus,* and *Emerita*), or to squat lobsters (such as *Munida*) than to true crabs (brachyurans). Lithodid crabs rank among the world's largest arthropods (invertebrates with articulate legs), and some species attain a leg span of 1 m.

Lithodids have ''tails'' or fan-shaped abdomens that are folded underneath the shell. Crabs have a pair of strong claws, three pairs of walking legs, and a pair of rudimentary legs used for grooming branchiae and egg-masses, or for sperm transfer. The female abdomen is distinctly asymmetrical, bearing four to six pleopods (modified legs) to which eggs are attached and carried during a variable period of time (up to 22 months). True crabs (brachyurans) have four pairs of walking legs and always a symmetrical abdomen, and females have four pairs of pleopods (swimmerets).

Lithodids are widely distributed in depth, from the intertidal as *Lithodes confundens* to the abyssal depths (4152 m) as *Paralomis bouvieri*. They typically inhabit the subpolar regions of both hemispheres. The high concentrations, size, and tasty flesh of king crabs promote their fisheries in different locations. In the North Pacific, landings of *P. camtschaticus* and the blue king crab *P. platypus* peaked at 74,000 tonnes in the early 1980s. In southern South America, the fishery for *Lithodes santolla* and *Paralomis granulosa* yields 3000 tonnes per year, and an exploratory fishery for *P. spinossisima* and *P. formosa* has been conducted off South Georgia and Shag Rocks. The gear used to fish for stone crabs is the baited trap.

Lithodids have a notable migratory pattern intertwined with mating, and associated with seasonal abiotic factors, mainly temperature, salinity, and photoperiod. They move in discrete groups that are often segregated into sex and size classes. Sub-Antarctic stone crabs migrate to very shallow waters for female moulting and mating in early summer. On average, Alaskan king crabs move 1 km per day and can reach up to 13 km per day, with a range of 12 km^2.

Deep stone crab *(Lithodes santolla)* from Tierra del Fuego. (Courtesy of David K. Barnes.)

Females moult under the protection of a larger male. Moulting is followed by mating: fertilization is external, occurring under the female abdomen. Females carry thousands of embryos for at least one year. Once these embryos are fully developed, they hatch as a swimming larva, which is morphologically different from an adult crab. Larvae undergo several body changes until they metamorphose into a juvenile crab, which settles to the sea bottom. Since crab exoskeleton is principally made of calcium, they moult their shell to grow. Moulting frequency decreases with age: juvenile crabs moult six to seven times during their first year and large adult crabs moult annually or even biennially. Lithodids can live up to 20 years.

Stone crab feeding habits vary with species, age, size, and depth. They are generalists (eating upon several items and mostly according to the environmental availability) and prey on snails, mussels, sea-urchins, squat lobsters, crabs, and algae. Stone crabs are also scavengers.

Lithodid crabs are the only representatives of "reptant" decapods (crabs and lobsters) that occur south of the Polar Front. In invertebrates low temperatures result in low metabolic rates and reduce their activity. Lithodids may tolerate constraints imposed by the cold and short periods of food availability at high Antarctic latitudes. Stone crabs have a prolonged brooding, and larval development is abbreviated and independent of external food. At hatching, larvae are provided with enough yolk to survive until metamorphosis and overcome the mismatch to the short period of food availability (planktonic algae). Larval hatching occurs over an extended period of time, not involving strong flapping movements of female abdomens, which would demand high energy consumption.

The family Lithodidae is of recent origin, arising between 25 and 13 Ma in the northeastern Pacific Ocean. Although the ancestor and primitive lithodids lived in the intertidal, radiation (diversification from an ancestral form to adaptively specialized forms) is thought to have occurred via deep cold water. Hence, tropical lithodids crossed the tropics into the temperate, sub-Antarctic (later), and Antarctic (recent) regions of the Southern Hemisphere. In the sub-Antarctic waters there are thirteen stone crab species, among which are the commercial *Lithodes santolla, L. confundens,* and *Paralomis granulosa*. In the Antarctic, from the eight recorded species, three still remain to be described for science. The most common Antarctic stone crabs are *L. murrayi* and *P. birsteini*.

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See also **Benthic Communities in the Southern Ocean; Bouvetøya; Cold Hardiness; Polar Front; South Georgia**

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DESICCATION TOLERANCE

Although survival of low temperature is perhaps the most obvious challenge to living in the Antarctic, the ability to survive the desiccating conditions of this cold desert is equally important. Most of the continent is permanently covered by snow and ice, and in its frozen form water is not available for organisms to use. This leaves only 1% of the continent, mainly the coastal regions, where there is ice-free ground and where melt water may be seasonally available during the brief Antarctic summer. Many of the organisms that are successful here are similar to those found in hot deserts. In fact, there is considerable overlap between the adaptations for cryoprotection and desiccation tolerance.

Some of the largest animals that can survive these extreme conditions are the cold-tolerant mites and springtails, but these are only a few millimetres long. The mite *Alaskozetes antarcticus* has a waxy cuticle, which reduces water loss. Mites and springtails are freeze avoiding and accumulate antifreeze compounds during the winter, which allow them to survive in a supercooled state. These compounds, such as glycerol, are also thought to aid water retention, while others, including trehalose, are known to protect membranes during desiccation. While the animal's body fluids remain liquid, in a supercooled state, they are susceptible to dehydration in a way similar to how uncovered food will dry in a domestic refrigerator. This occurs because the water vapour pressure of the animal's supercooled body fluid is higher than that of ice in the environment, even at the same temperature. This loss of water causes an increase in the solute concentration of the body fluids and a reduction in the diffusion gradient until a state of equilibrium is reached. If the temperature reduces further, more water will be lost. Some animals, such as the Arctic springtail *Onychiurus arcticus,* synthesise high concentrations of trehalose from glycogen stores, enabling them to survive the loss of 80% of their water. Desiccation protects against freezing, as without water they cannot freeze. However, organisms that can survive freezing are not susceptible to desiccation.

Many plants and microscopic animals survive the Antarctic winter in an anhydrobiotic state and remain dormant until water becomes available. Few higher plants survive in this way, but some mosses, lichens, algae, and cyanobacteria can exist without water for long periods. Some of these produce specialised proteins called dehydrins, which are responsible for the production of compounds that protect cells from damage during desiccation. A feature of these organisms is that they can survive even rapid drying and can recover in a matter of minutes. Other organisms change their physical form during periods of drought to reduce water loss. Nematodes, such as *Panagrolaimus davidi,* coil during desiccation, while some tardigrades form a tunlike structure. The macroalgae *Prasiolla crispa* has thick cell walls and an absence of vacuoles, which enable it to survive up to 90% water loss. As it dries its form changes from a crinkly lettuce leaf to a thin, polythenelike structure. In this form it maintains a slightly moister environment beneath it where microarthropods can survive. Some snow-free areas of the Antarctic continent, such as the Dry Valleys, receive very little precipitation. Here, only the most desiccation-resistant organisms, such as nematodes, rotifers, and tardigrades, are found.

ROGER WORLAND

See also **Algae; Anhydrobiosis; Dry Valleys; Lichens; Microbiology; Mosses; Nematodes; Parasitic Insects: Mites and Ticks; Rotifers; Springtails; Tardigrades**

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DISCOVERY INVESTIGATIONS (1925–1951)

The Discovery Investigations were initially intended to research scientifically the biology of whales in the Atlantic sector of the Southern Ocean in order to conserve the whaling industry in the area of the Falkland Islands Dependencies. The work was funded by a tax on all whale oil produced in the Dependencies. Shore-based whaling started in South Georgia in 1904, and a suspicion that whales were being overfished was being voiced by 1910.

An advisory interdepartmental committee, set up by the British government, recommended an executive committee to manage a scientific expedition to investigate the total ecology of whales in the South Atlantic. Ernest Rowland Darnley of the British Colonial Office and Dr. Sidney Frederick Harmer, keeper of zoology at the British Museum (Natural History), became chairman and vice chairman, respectively, of a committee that oversaw the equipping, staffing, and execution of the investigations.

The first ship chosen for the scientific work was *Discovery,* built for the British National Antarctic Expedition (1901–1904), which gave her name to the Committee. Her captain was Commander Joseph Russell Stenhouse. Dr. Stanley Wells Kemp was the director of research from 1924 to 1936 and overall leader of the investigations. Two further purpose-built ships were employed: *William Scoresby,* initially intended to mark whales with retrievable darts to show the migration and movements of the population, and *Discovery II,* an oceanographic research ship equipped with up-to-the-minute technology. To enable anatomical and analytical studies to be made, a laboratory with residential accommodation was built at Grytviken, South Georgia, near the whaling station. This enabled scientific investigation of whale carcasses. Work there also included analysis of sea water and the fauna of South Georgia.

In the first three years of the program (1925–1927), *Discovery* investigated the environment of the whales, including their food and its distribution, taking water samples regularly. They visited South Africa, South Georgia, the Falkland Islands, the South Orkney Islands, the South Shetland Islands, and the Bismarck and Gerlache straits. The farthest point south was 64°58′ S. They took measurements between Deception Island and Cape Horn. *Discovery* proved unsatisfactory as an oceanographic research vessel and was replaced in 1929 by *Discovery II*.

The results of the investigations laid the foundations of almost all Southern Ocean science. The scientific papers resulting from the work were published in *Discovery Reports,* twenty-five volumes before 1949 and twelve more by 1980. The external details of the size and proportions of the principal species of whales were defined, together with their life histories, details of breeding, pregnancies, periods of lactation, and growth rates. Their summer diet in the Antarctic was defined and their parasites described. The seasonal migration of humpback whales and the segregation of their different communities was established, as was the tendency for blue and fin whales to return to the same Antarctic areas.

As a result of this knowledge gained, it became apparent that it would be useful to study the oceanography of the Southern Ocean. The origin of water masses was accounted for, and variations caused by geographical features were mapped. The effect of wind on currents was estimated together with the actual and relative speed of water movements. The important effect of the Weddell Sea on the Southern Ocean, and the formation and distribution of bottom water, was demonstrated. They also mapped the Antarctic Convergence. The concentration, distribution, and circulation of nutrient salts were described and mapped. The detailed topography of the Scotia Arc and its hydrological and geological significance were explained.

They surveyed the plankton in detail and found out what influenced its growth and migration. Intensive studies of krill established that it migrated vertically as well as horizontally and had connections with the movement of plankton in general. Detailed information was gained of the oceanographic conditions around South Georgia and the South Shetland Islands.

Although it was not a surveying expedition, surveys were made of the South Sandwich Islands, the South Orkney Islands, and the South Shetland Islands, and some of the coastline of Queen Maud Land, Kemp Land, and Mac.Robertson Land was surveyed and sounded. Visits were made to remote islands such as Tristan da Cunha, Marion, and Campbell islands.

A few surveys were made outside the Southern Ocean, including one of the Peru Coastal Current, a trawling survey of the Patagonian Continental Shelf, and lines of deep-sea stations at 30° W from the Antarctic to 15° N, and one on the eastern side of the Indian Ocean to 10° N.

A large collection (thirty thousand jars) of specimens of marine fauna was made and stored at the Natural History Museum, London.

The ships were occasionally used for assistance to explorers. Sir Hubert Wilkins made use of *William Scoresby* when exploring Graham Land in 1929. *Discovery II* was used twice. On the first occasion, in 1934, it met *Bear of Oakland* in the Ross Sea in order to exchange Richard E. Byrd's expedition doctor, who had dangerously high blood pressure, for a relief doctor from New Zealand. The second rescue, in 1936, was to collect Lincoln Ellsworth and his pilot Hollick Kenyon from Little America, when they were supposedly lost after flying across Antarctica.

The active part of the research work was suspended during the Second World War, although N. A. Mackintosh, then director of research, continued desk work in the UK. A small subcommittee chaired by James M. Wordie advised on the organization of Operation Tabarin, a British Antarctic operation set up towards the end of the War. *William Scoresby,* then a minesweeper based in the Falkland Islands, was used as transport. Operation Tabarin ultimately developed into the British Antarctic Survey.

By 1949, the ships had not been returned by the government for use after wartime requisitioning. The Discovery Investigations were therefore absorbed into a new organization, the National Institute of Oceanography. This organized *Discovery II*'s sixth commission, a second winter circumnavigation.

Rosalind Marsden

See also **Antarctic Bottom Water; Antarctic: Definitions and Boundaries; Blue Whale; British National Antarctic *(Discovery)* Expedition (1901–1904); Campbell Islands; Ellsworth, Lincoln; Fin Whale; Humpback Whale; Polar Front; Ross Sea Party, Imperial Trans-Antarctic Expedition (1914–1917); Scotia Sea, Bransfield Strait, and Drake Passage, Oceanography of; Sealing, History of; Seals: Overview; South Georgia; South Orkney Islands; South Sandwich Islands; South Shetland Islands; Southern Ocean; United States (Byrd) Antarctic Expedition (1933–1935); Weddell Sea, Oceanography of; Whales: Overview; Whaling, History of; Wilkins, Hubert; Wordie, James; Zooplankton and Krill**

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DISEASES, WILDLIFE

Disease can be due to parasites, viruses, bacteria, or fungi that invade the tissues of an animal to visibly and deleteriously affect its health.

Very little is known of diseases in populations of seals and birds in Antarctica although they are known to be prone to a wide range of diseases in captivity. Reported occurrences are rare and it is not known whether the infective agents are native or nonindigenous. It is likely that infective agents are present among populations but diseased individuals appear not to be observed. As healthy animals can carry low levels of potentially harmful organisms without succumbing to disease, such subclinical disease is hard to detect as its symptoms may be confused with other conditions such as starvation. Further, the problem of detection is great in Antarctica and even on the sub-Antarctic islands where there are few observers and the animal populations are located remotely from human activity.

Ectoparasites are found on most species. The flea *Glaciopsyllus antarcticus,* which infests Antarctic fulmars *Fulmaris glacialoides* and snow petrels *Pagodroma nivea* is the only flea found on the Antarctic continent. Several species are found among sea birds of the sub-Antarctic Islands. The tick *Ixodes uriae,* which can transmit disease, is widespread among sub-Antarctic sea birds but is absent from those breeding on the Antarctic continent. Heavy infestations of ticks, particularly on chicks, can affect survival even in the absence of disease. Ectoparasites infesting seals include sucking lice and nasal mites.

Gastrointestinal nematodes and cestodes appear widespread in a number of species of birds. Burdens of these endoparasites tend to be heaviest in juvenile birds and generally only contribute to mortality when combined with starvation or other forms of stress. Blood smears from a number of wild Antarctic and sub-Antarctic species of bird have been examined for the presence of parasites. Except for a hematozoan *Hepatozzon albatrossi* in the blood of three albatross species on South Georgia, all tests have been negative.

Avian cholera *Pasteurella multocida* was reported as the cause of death in the brown skua *Catharacta lonbergi* on Livingston Island, rockhopper penguins *Eudyptes chrysocome* on the Campbell Islands, chinstrap penguins on South Georgia, and the yellow-nosed albatross *Diomedea chlororhynchos* on Île Amsterdam. A variety of bacterial species of unknown pathogenesis but including *Escherischia coli* and *Salmonella* sps. have been isolated from Adélie penguins *Pygoscelis adeliae* and skuas *Catharacta maccormicki* in the Ross Sea region. *Campylobacter* spp. have been isolated from skuas, penguins, and albatrosses on Bird Island, South Georgia. The zoonosis Lyme disease is caused by the spirochaete *Borrelia burgdorferi,* which is carried by sea birds transmitted by *Ixodes* ticks. It has been found through DNA analysis in ticks on the Campbell Islands and Îles Crozet. King penguins on Îles Crozet have antibodies to *B. burgdorferi*. There is evidence to suggest that emperor and Adélie penguins near Mawson Station and penguins, skuas, and albatrosses on Bird Island have been exposed to *Chlamysophylia psittaci,* which causes psittacosis (ornithosis).

Several mass mortalities have occurred in penguin colonies. All have been localised to single colonies and single species, and appear to be self limiting. Causal agents were not identified. Gentoo penguins *Pygoscelis papua* on Signy Island were reported with symptoms resembling the virus disease puffinosis found in several Northern Hemisphere sea birds. Adélie penguin chicks, seemingly well fed, were found dead and dying near Mawson Station. A loss of normal muscular coordination (ataxia) was observed before death.

The presence of antibodies suggests that several species have been exposed to viral or bacterial agents that can cause disease. However, there is no evidence to suggest that any clinical expression of these diseases has occurred. Antibodies to avian paramyxoviruses (APMV) and Avian Influenza (AI) appear widespread and persistent among Adélie penguins and skuas in Antarctica. Antibodies to Newcastle disease virus (NDV), a paramyxovirus, have been found in Adélie penguins. Either AI or NDV, if present as a virulent strain, could be catastrophic for avian populations. Antibodies to Avian Influenza (AI) virus have been found in Adélie penguins at Casey Station and in skuas in the Ross Sea region; no actual virus particles have been isolated from those birds. Antibodies to flaviviruses have been found on several species of sub-Antarctic birds. Infectious bursal disease virus (IBDV) serotype 1 appears endemic in Adélie penguin, emperor penguin, and skua populations.

Among seals, antibodies to canine distemper virus (CDV) (a morbilli virus) have been found in crabeater seals *Lobodon carcinophagus* and leopard seals *Hydruga leptonyx* but not Weddell seals *Leptonychotes weddelli* at the Antarctic Peninsula. Antibodies against European phocine herpes virus were detected in Weddell and crabeater seals in the Weddell Sea. These seals were suffering from respiratory disease at the time and titres in some animals were high, suggesting that the symptoms may have been due to the virus. No antibodies to influenza A have been detected in Antarctic seals despite its presence in the birds. Anti-Brucella antibodies were found in Antarctic fur seals and Weddell seals at Cape Shirreff. Brucellosis is a zoonotic bacterial disease that can cause abortion in affected animals. Approximately 1500 crabeater seals were found dead in 1955 in the Crown Prince Gustav Channel to the northeast of the Antarctic Peninsula. A contagious viral disease was suspected but no samples were taken or pathological investigations made. A mass mortality of fur seals occurred on the Auckland Islands in 1988. No definitive cause was determined despite extensive tests.

The significance of finding antibodies to a number of viruses and bacteria known to cause infectious disease elsewhere is uncertain. It does not follow necessarily that the animal has actually suffered from the disease. The host species could have been exposed in the recent past to the specific disease-causing agent or alternatively to a serologically related but nonpathogenic strain. This latter case may provide some cross-immunity to the pathogenic strain.

It is likely that most disease outbreaks will be due to organisms now endemic in the populations. There are also many natural pathways, for example, through migratory species, for the potential introduction of disease-causing organisms. Human activity also has the potential to introduce diseases or help spread them from one site to another, though there is no evidence that this has occurred to date. Vigilance is required to ensure that increasing human activity does not introduce infectious agents or contribute in other ways to the development and spread of disease.

KNOWLES KERRY

See also **Albatrosses: Overview; Amsterdam Island (Île Amsterdam); Antarctic Fur Seal; Antarctic Peninsula; Campbell Islands; Chinstrap Penguin; Crabeater Seal; Crested Penguins; Crozet Islands (Îles Crozet); Emperor Penguin; Fungi; Gentoo Penguin; King Penguin; Leopard Seal; Microbiology; Nematodes; Parasitic Insects: Lice and Fleas; Parasitic Insects: Mites and Ticks; Penguins: Overview; Seals: Overview; Skuas: Overview; Snow Petrel; South Georgia; Weddell Seal; Yellow-Nosed Albatross**

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DIVING—MARINE MAMMALS

The essential concepts of diving biology revolve around one central issue: how do marine mammals remain underwater for such a long time while exercising? This seems contradictory to us as a terrestrial species: if humans wish to extend their ability to breath-hold, they remain as quiet as possible. The equivalent idea would be for humans to perform aerobics while breath-holding. Add to this the problem of withstanding extreme pressure from diving and, in polar regions, where water is at freezing temperatures, and it becomes a very interesting question how marine mammals dive.

To approach this question, we need to think about what is "normal" for a marine mammal. For these animals, they must be able to navigate, find food, in many cases reproduce, vocalize, and migrate while underwater. In fact, for species that rarely come to the surface, it might be easier to classify them as "surfacers" rather than divers—that is, being underwater is "normal" and being at the surface is relatively infrequent. Thus, their environment is not extreme to them, because they have adapted to those conditions over millions of years. With that perspective, it becomes easier to compare terrestrial and marine mammals and explore the nature of diving.

Maximum Diving Depth and Duration for the Different Pinniped Species That Live Near or in Antarctic Waters.

Species	Maximum Depth (m)	Maximum Duration (minutes)
Weddell seal	700	92
Crabeater seal	713	24
Ross seal	372	11
Southern elephant seal	120	1500
Antarctic fur seal	100	10

All of these data were collected with versions of time-depth recorder (TDR) technology.

By itself, diving in polar regions is not different from diving in the tropics in terms of fundamental biological adaptations. However, the additional factors of cold water, dealing with sea ice, and living through months of complete darkness add difficulties to the marine system. In spite of these problems, most of the detailed physiology and biochemistry of diving have been discovered in Antarctic studies.

We should begin by exploring some of the methods that are *not* used by diving mammals to remain underwater for long periods.

The primary marine diving mammals are whales, seals/sea lions, and dugongs/manatees. There are also other diving species that live near the sea, but usually don't dive as well (polar bears, sea otters). All of these animals are mammals, like humans, dogs, cats, cows, and elephants. They do not have gills like fish, they cannot breathe underwater through their lungs, nor do they absorb oxygen through their skin like some amphibians. They must take all the oxygen with them from the surface and use it at such a rate that they have enough oxygen to make it back to the surface. They need oxygen like other mammals and don't have any significant biochemical adaptations that would allow them to live without it. They do not hibernate underwater nor reduce their body temperature to such a low level that they do not need to use oxygen at normal rates. In fact, for the most part, they have a body temperature (37°C) very close to that of humans and maintain that temperature even in polar waters below freezing (–1.8°C). This is an important point because of the well-known cases of human children falling into ice-cold waters for long periods and not drowning. The children essentially shut down their need for oxygen by being extremely cold and thus survive what could have been a lethal event. While there are some components of diving biology involved in these cases, the primary event is that their entire body becomes very cold and their need for oxygen drops significantly. Marine mammals must stay alert underwater, swim, exercise, vocalize, digest their meals, and perform a host of other behaviors that require them to stay warm.

A more surprising aspect of diving is that the amount of oxygen carried in the lungs of most divers is not an important part of their diving ability. Again, this is contrary to the human response of taking a large breath before swimming underwater. In many cases, marine mammals exhale before diving. There are a variety of reasons for this particular adaptation, but complications dealing with the extreme pressure of diving and how that would impact air in the lungs seem to outweigh the need to carry oxygen in the lungs for use underwater. It turns out that they carry most of the oxygen they need in the blood and in the muscles.

Finally, we know most about diving in seals and sea lions because of our ability to work with them in the field and in laboratories. We know much less about manatees and even less about whales. We can watch all of these species from the shore, from planes, boats, and other platforms. We can put dive recorders on them to time their dives and track their locations. But even the simple question of asking the heart rate of a diving sperm whale while underwater at a mile deep becomes a major technical challenge.

If these are many of the aspects of how marine mammals don't dive, we can more easily turn to the question of what mechanisms they do utilize to dive underwater and what we know about marine mammal diving from the Antarctic.

In order to dive for long periods, there are primarily two levels of adaptation that have been successfully utilized by the diving mammals: maximize the amount of oxygen carried and use it more slowly. In both of these areas, fundamental studies of the mechanisms involved have been carried out in the Antarctic, mostly with Weddell seals *(Leptonychotes weddellii)*. Weddell seals are superb divers (the duration record is over 90 min) and are able to dive very deeply (up to 700 m or more). They are large seals, are easy to approach and handle, occur in large numbers near their rookeries, and spend a great deal of time on the frozen ice surface. The unique features of their behavior and habitat have made them the most studied of all marine mammals for diving physiology under natural conditions.

The study of diving Weddell seals began with Gerald Kooyman, at the Scripps Institution of Oceanography. In the late 1960s, he was a graduate student, working at McMurdo Station on Ross Island in the Ross Sea. He observed Weddell seals on the ice and noted that they seemed to dive for very long periods (over 20 min). Eventually, he built a homemade dive recorder and found out that the seals could dive for over 40 min and up to several hundred meters deep. This was a revolutionary result and he found it hard to convince the scientific community with such simple devices. Thus began a 30-year program of research for him in the Antarctic working with Weddell seals and other superb divers, such as the emperor penguin. His laboratory built more sophisticated recording devices to attach to the seals and also described a unique method of conducting detailed physiological diving studies on the seals.

McMurdo Sound is seasonally covered with ice for at least 20 miles away from the research station. This ice is about 2 m thick in normal years and forms a stable platform for research, logistics, and travel. The Weddell seals move into this area in late August to begin their breeding season and do so by exploiting natural cracks in the ice, which they use as breathing holes and for accessing the surface to rest. By early November, hundreds of them are on the ice within 10 miles of McMurdo Station. Kooyman put a 1-m-diameter hole in the ice about 5–6 miles offshore and far away from other cracks. He constructed a hut over the hole and equipped it with a variety of medical and research tools for studying the seals. His team would then capture a seal near the shore and bring it to the hut. Once there, they could put on diving monitors and release the seal into the hole. The seal could dive, swim, sleep, or rest, but it would always have to come back to the hole to breathe, unless it found a way out and escaped back to the shore. Using this method, Kooyman was able to resolve fundamental issues such as breathing rates while recovering from dives, diving lung volume, heart rate during initial dive descents, and a suite of other fundamental aspects of diving recovery. He and Bob Elsner, also from Scripps, studied pregnant Weddell seals at isolated holes and determined how fetuses responded to long-duration diving of the mother. By the late 1970s, Kooyman's laboratory was building very sophisticated Time–Depth Recorders (TDRs), which were able to trace diving duration and depth for up to two weeks. He initially put these devices on seals in the huts, and then on seals at the rookeries. The combination of these innovations, the isolated diving hole and the TDR, revolutionised the field of diving physiology and biochemistry. Both of these methods continue to be used for diving studies in the Antarctic and the manufacture of TDRs is now a competitive business with companies producing smaller, lighter, and more powerful devices. Needless to say, the original TDRs are obsolete relative to their electronic descendants. But their origins were on the ice, in the Antarctic.

From the pioneering work of Irving and Scholander in the 1940s, models of how diving mammals functioned had been built on laboratory studies at Universities and other research sites. They proposed the dive reflex theory, which suggested that marine mammals could alter blood flow during the dive such that the oxygen-rich blood would be redirected to the more central organs (heart, lung, brain) and heart rate would decline while the animals were submerged. They postulated that the peripheral organs (muscle, liver, kidney, etc.) received relatively little blood flow and thus became oxygen limited. As supporting evidence, they documented the increase in lactic acid in the blood (a waste product of metabolism that occurs when oxygen is low). Scholander later referred to the refined ability in marine mammals of redistribution of blood flow as a component of the "Master Switch of Life." Kooyman noted that Weddell seals could dive many times in a row without much time at the surface to recover. This seemed at odds with the dive reflex theory, which held that seals stay at the surface to restore their oxygen levels and to metabolize the lactic acid that has built up in their blood.

In an early isolated hole study, Kooyman found that heart rate would drop in Weddell seals during diving, as predicted by Scholander, but not in the expected pattern: during short dives, the heart rate stayed relatively elevated while longer divers had lower heart rates. Could it be that the dive reflex could be modified by the seal depending on the length of the dive? By 1977, Kooyman had designed a study where seals were taken to the isolated diving holes and simple blood-collecting catheters were placed in the animals along with TDRs. He and his colleagues found that short dives (less than about 20 min) did not show the expected increase in lactic acid, but lactate appeared in longer dives in a graded manner. Further, the longer dives had correspondingly longer recovery times at the surface in order to remove the lactic acid from the blood. It appeared, at least with Weddell seals diving in these experiments, that they did not use the Master Switch as described by Scholander, but more accurately used a "Master Dimmer Switch"; they could tune the strength of the diving response to the nature of the upcoming dive. Long dives required a strong response so that they could remain underwater for long times. Short dives did not. The dive duration break point was named by Kooyman the Aerobic Diving Limit (ADL) and was defined as the dive time under which lactic acid would not appear in the blood after the dive.

Armed with this information, the Kooyman team returned to McMurdo, but this time worked only with seals at their natural haul-out sites. They placed dozens of TDRs on seals and left them alone for up to

2 weeks. On recovering the devices they found that about 95% of the natural dives were shorter than the ADL. Further, the surface recovery time followed the same pattern: short dives had short recoveries, while longer dives had longer recoveries. ADL theory is now the most accepted model of diving physiology and has been cited hundreds of times on multiple species.

Once the TDR and the isolated diving hole method became accepted by the scientific community, the number of studies using them increased and the studies became more complex. Warren Zapol from Boston (Massachusetts) General Hospital developed sophisticated surgical methods and diving devices that could be used to collect blood samples from Weddell seals while they were diving at depth. They found that the seals apparently altered the amount of oxygen in the blood while diving, perhaps by controlling the number of blood cells that were in circulation during a dive. They also monitored the body temperature of Weddell seals while they were diving and found the seals cooled down by a few degrees. As previously discussed, cooling can help lower the need for oxygen, and this allows the seals to dive longer. Eventually, students of Kooyman (including the author) adapted the isolated hole methods to our own questions: I and my students explored the nature of how Weddell seal pups develop their diving abilities, what happens when they sleep (it turns out they hold their breath while sleeping), and how they digest their meals when they successfully capture fish or squid. Randall Davis from Texas A&M developed small and robust seal-mounted cameras that have shown us how Weddell seals navigate and find and capture their prey underwater. Terrie Williams (a Kooyman postdoctoral fellow) from the University of California at Santa Cruz (UCSC) has discovered fundamental swimming adaptations (gliding and stroking balance) that allow the seals to be extremely efficient underwater and thus conserve the precious oxygen they carry with them. Paul Ponganis, also from Scripps, has taken the isolated hole technique and applied it to study diving in emperor penguins in the Ross Sea. Elsner and Wartzok used isolated hole studies to examine how Weddell seals navigated under the ice.

The Antarctic has provided a rich seam for the study of diving in seals, but what about the diving biology of whales? Most diving studies of whales cannot be conducted using the methods developed for seals, but since whales share many of the features of seals, even the studies of seals have provided an important guide to the biology of diving in whales. There is still a lot of potential to work on diving mammals in Antarctic waters. Experiments based on the isolated-diving-hole paradigm are becoming more complex and providing deeper knowledge of the physiological, biochemical, and medical bases for diving.

MICHAEL CASTELLINI

See also **Antarctic Fur Seal; Crabeater Seal; Leopard Seal; McMurdo Station; Ross Sea; Ross Seal; Southern Elephant Seal; Weddell Seal**

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DOGS AND SLEDGING

Dogs

For thousands of years, dogs have been pulling the sledges of the Inuit in the Arctic. It was therefore not surprising that the first party to winter on the Antarctic continent in 1898, Carsten Borchgrevink's *Southern Cross* expedition, took dogs. Otto Nordenskjöld's Swedish expedition used dogs very successfully in 1901 on the Larsen Ice Shelf with a journey of 380 miles. However, they proved of much less value on the British National Antarctic Expedition (1901–1904) under Robert Falcon Scott and on Ernest Shackleton's expedition on *Nimrod* (1907–1909). Little did the British realize at the time that this was due more to their inexperience in training and driving dogs than to the capabilities of the animals.

Roald Amundsen's magnificent journey to the South Pole in 1911 proved beyond a doubt that dogs were the best means of pulling loads in the Antarctic. He took ninety Greenland dogs plus twenty pups to his base at the Bay of Whales in the Ross Sea. He eventually took four thirteen-dog teams on his main southern journey, each pulling slightly more than 1000 pounds, except for the lead team, which had a load about 100 pounds lighter. Twenty-four of Amundsen's dogs were killed at the top of the Axel Heiberg Glacier and fed to the men and other dogs. In total, forty-one dogs were killed, and the party returned to the base at Framheim with eleven very fit animals having covered 1860 miles in 89 days. When Amundsen reached Hobart, Tasmania, he ended up donating twenty-one dogs to Douglas Mawson's Australasian Antarctic Expedition (AAE), although these did not engage in extensive work on the AAE, as they were in the Antarctic only for the second year, in which much less sledging was undertaken.

In contrast to Amundsen's efforts, none of the two British expeditions of the Heroic Age gave such an important place to dog transport. Scott's first expedition had thirty-three smaller Western Siberian Ostiak-type dogs, plus two Greenland dogs presented by the American Arctic explorer Robert E. Peary and one New Zealand collie bitch. Shackleton took a small number of Siberian huskies but concentrated his efforts on his ponies; the dogs only came into their own on Ernest Joyce's depot-laying trip late in the expedition. On Scott's second expedition, he intended to use ponies, motor transport, and, most importantly, man-hauling, as well as his thirty-three Siberian huskies. Shackleton's Imperial Trans-Antarctic Expedition planned to cross the continent relying on dogs, but was halted in the Weddell Sea. Mawson's AAE originally obtained fifty Greenland dogs, although only twenty-eight remained alive by the time they established the main base at Cape Denison.

After this mixed start, dogs remained the main form of transport for British expeditions in the mountainous landscapes of the Antarctic Peninsula until the mid-1970s. As tractors, ski-doos, and aircraft became more reliable, they gradually replaced dogs. Americans relied entirely on mechanical transport in the 1950s, although more than 100 dogs had supported the pioneering flying efforts of Richard E. Byrd's first expedition.

Dogs were finally banned from the Antarctic, officially on environmental grounds, under the 1992 Protocol on Environmental Protection to the Antarctic Treaty. The last fourteen dogs left the British base at Rothera on the Antarctic Peninsula on February 22, 1994.

British Sledging and Dog Expertise

The greatest impetus to Antarctic dog-sledging came with the British Graham Land Expedition (BGLE) (1934–1937). John Rymill's party brought with it the skills and techniques of the Inuit from Greenland, where Rymill, W. E. Hampton, Quinton Riley, Alfred Stephenson, and Edward Bingham had all been with Gino Watkins on the British Arctic Air Route Expedition. Bingham, as well as being surgeon, was also in charge of the dogs. They traveled extensively down King George VI Sound and proved that the Antarctic Peninsula was part of the mainland without channels across to the Weddell Sea. They showed that it was possible to travel safely with dogs and to use them for support for surveying and scientific work for extensive periods of time.

In 1945, the British brought dogs down from Labrador, establishing them at Hope Bay and later at Stonnington in Marguerite Bay. Bingham was in charge at Stonnington and gave that continuity from the Inuit via the BGLE. The pattern remained basically unchanged for the next 50 years. Most members of the Falkland Islands Dependencies Survey (later the British Antarctic Survey) spent two and a half years working in the Antarctic. During their first year, they were "apprenticed" and picked up skills and knowledge about a broad range of areas, including dogs and sledging. After that, they were able to pass on their skills and experiences. Through this system, a well-tried and relatively safe method of traveling was developed.

Several species of dogs were used, each with distinct characteristics and suitable for different roles. Siberian, Alaskan malamute, and Samoyed dogs were used, but Greenland/Labrador dogs—also known as polar Eskimo dogs or, more recently, Inuit dogs, Canadian Inuit dogs, or Quimmiq—proved by trial and error to be the best for the common "freighting" type of work. Generally in the Antarctic, the term "husky" referred to the Greenland breed. Greenland/Labrador dogs were used almost entirely after 1945, and by inbreeding a distinct Antarctic husky developed. These were strong, short-legged, had a short but thick coat, and had a temperament to pull for hours, days, and months in both summer and winter conditions. They typically measured some 23 inches in height to the shoulder, about 60 inches from nose to tail, and had a shoulder width of about

10 inches, a hip width of 8 inches, and a weight (for males) of about 90 pounds. Their long, bushy, curled tail was essential in protecting the head and paws of the dog when curled up in a blizzard. They came in a variety of colours, although darker dogs suffered in the summer heat. Traveling at night in the summer helped to overcome this heating, and the freezing of soft surfaces at night was beneficial for travel.

Bitches came on heat every six months with a gestation period of 63 days. They had an average of four to six pups, with a record of fourteen. The litters were sometimes born on long journeys, with successful survival rates. The pups needed to be handled constantly to establish a relationship with men. They were fed minced seal meat, vitamins, and cod liver oil. The pups joined the team at 12 months; if they did earlier they were more likely to develop osteoarthritis in later life. New blood was introduced from Greenland to prevent over-inbreeding. Each dog was registered with an individual dog card showing its good and bad characteristics, progress, etc. In theory only the best dogs were used in the breeding programme.

In training, a lead dog and the front pair were selected and trained to words of command. The dog teams normally consisted of seven or nine dogs, expected to pull their own weight. Numerous styles of hitching dogs to the sledge have been used, the most common being a centre tandem trace or a modified Greenland fan trace. The centre trace was used most and was more efficient mechanically. Fan traces give more freedom and allow the team to develop more naturally as a "pack" and perhaps lead to a more contented team. They also give freedom to negotiate ice floes on sea ice. However, a fan trace can become badly tangled. The modified BGLE fan was a good compromise.

The words of command were adopted with the first set of dogs in 1945. When the last Antarctic dogs were given to the Inuit at Inukjuak on Hudson Bay, they immediately recognized the commands, which had not changed in 50 years. These were:

- To start: "Up dogs, away you go"
- Faster: "Huit, huit, huit"
- Turn left: "Irra, irra, irra"
- Turn right: "Auk, auk, auk"
- Slow down: Long, drawn-out "Ah now"

Harnesses were made of 1.5-inch lampwick as used on oil paraffin lamps and introduced by the BGLE. This material is soft and prevents chafing. It can easily be sown and adjusted, which is essential to avoid a dog's falling out of a harness in a crevasse incident. Harnesses need to be dried in the apex of the tent on journeys. Whips were rarely used. Rope thumpers were used to break up dog fights.

A king or alpha dog naturally developed in each team or pack. The king dog was normally tethered at the rear of the hitch where he could command those in front. He eventually would be challenged by a younger dog. The lead dog was usually the most intelligent one. Often a bitch was chosen. As dogs can weight 20–30 lbs more than bitches, one did not want to lose the extra pulling power, as a lead dog did not pull as much as the other dogs.

When not working on base, dogs were fed 6 lbs of seal meat every other day. The blubber on the meat was fed to the dogs in winter but removed in the summer. Initially, while sledging, they were fed dehydrated meat, pemmican, and, later, Nutrican. These gave 2000–3000 calories. Work by Dr. Henry Wyatt and Dr. Neil Orr in the 1950s showed that this dehydrated food was inadequate. Working huskies need closer to 6000 calories per day. Gutted seal meat proved the ideal food, and, as huskies are coprophagic, little food was wasted. Water was only given to them in summer when snow was unavailable at some bases.

Short names were chosen, like for working sheep dogs. Teams of seven to nine dogs were also named, and these were passed down from driver to driver. The last two teams in the Antarctic were the Huns and the Admirals, and two small peaks on Alexander Island are named after them. The Admirals were formed in 1958, and so lasted 36 years with sixteen drivers and thirty-nine dogs.

Travelling

A team of seven dogs and two bitches should pull a load of 770 lbs, assuming they can pull their own weight. Dogs respond to a routine. It was normal to travel around 50 minutes with a 5- to 10-minute break. They traveled around 3–4 miles per hour, about the speed of a human trotting, but all depended on surfaces, loads, and the fitness of the team. They could make 30–45 miles a day on a good surface, with an average being 10–15 miles. With relaying on bad surfaces, 2–5 miles might be all that could be achieved. These figures are based on heavy loads.

Various techniques were used to get the most out of a team, especially towards the end of the day. A common technique was to put bells on the lead dog for the last hour. The pack associated this with rest and food. It was essential to check the dogs at night if there was a blizzard or heavy snow to ensure that they did not suffocate and were not strangled, as they were tied to night stands.

The lead dog was supposed to be able to lead without a human in front. This was especially important in crevassed country, as a dog can give warning of crevasses, or if one falls down a crevasse it can be rescued much more easily than a man.

The dogs had a working life of 6–7 years, with an exceptional leader working up to 9 years. They began to suffer from arthritis and sometimes the coats of the older dogs would become thin, losing their insulation. One of the saddest jobs of a dog-driver was at the end of the season deciding which animals had to be culled. To shoot a friend and companion who had pulled a sledge for 1000 miles was very hard. However, it was essential to have new, young blood joining the teams. Some old dogs with unique records were allowed to retire to static island bases and perhaps be involved in a breeding programme. Very few came back to Britain, although Sir Vivian Fuchs had his old lead dog Captain in Cambridge, an entire team of dogs put in 2000 appearances at the Festival of Britain in 1952–1953, and a few returned to help breeding of husky dogs in the UK. Equally, a few were given to or exchanged with other nations in the Antarctic.

Dogs sledged in winter temperatures of –40°F. They suffered, but continued to work hard providing they were well fed. Heavy snowfalls on the western side of the Antarctic Peninsula were always a challenge for sledging. On northern Adelaide Island, 12-foot survey poles disappeared in three months. Dogs were expected to work throughout all of this. Dogs can suffer from scurvy, but this was overcome by feeding them fresh seal meat. Blocked intestines and gynecological problems were also revealed in post-mortems carried out by doctors with the assistance of the dog-drivers.

Some Dog Facts

There were a total of 900 dogs used by the British Antarctic Survey, of which about 850 were born in the Antarctic. About forty dogs were lost in crevasses, twenty-five drowned, and thirty lost to fights and natural causes. The longest unsupported journey by members of the British programme was 700 miles in 67 days in 1947. The average distance covered by an individual dog in a career was 3000 miles. The longest distance sledged in the life of a dog was 14,440 miles by Mac and Bryn, born at Hope Bay in 1958.

Dogs were also a component of the first crossing of the continent, the Commonwealth Trans-Antarctic Expedition (CTAE), led by Vivian Fuchs. The dogs had originally come from the Antarctic Peninsula, and Ken Blaiklock and John Stephenson were with the first dog team to reach the South Pole since Amundsen in 1911.

Between July 1989 and March 1988, the International Trans-Antarctic Expedition carried out the longest supported dog journey. They traveled from the north of the Peninsula, along the spine to the South Pole, across to Vostok Base, and finally to the Russian base on the coast at Mirnyy. The expedition was led by Will Steger and Jean-Louis Etienne, but Geoff Somers, a former member of BAS on the Antarctic Peninsula, was in charge of logistics and dogs.

Other nations made journeys with dogs that were equally notable to those of the British. On the Peninsula, the Argentines made long journeys from Esperanza to their base at San Martine in Marguerite Bay. The New Zealanders used dogs they obtained from the Australians and from Greenland to support the CTAE. In 1960, Wally Herbert was commissioned by the New Zealand programme to find a dozen Greenland dogs. Within three years, they had four teams of nine dogs plus a number of backup animals. These were used extensively in the region of the Axel Heiberg Glacier and in northern Victoria Land until tractors began to take over.

The Australians obtained dogs that had been used by a French expedition and left in a Melbourne zoo in 1949. These were subsequently used at Mawson, Davis, and Casey stations. They were especially useful for travel on sea ice in connection with biological studies. The last dogs left Davis in 1965, Casey in 1970, and Mawson in November 1992.

Japan kept dogs at Syowa Station between 1956 and 1959. In February 1958, the relief ship could not get closer than 60 miles, and weather prevented them from flying in a new wintering party. The fifteen dogs had been fed and left awaiting that new party. Somehow two of these dogs survived the winter without humans on base. One of these dogs, Taro, returned to Japan a hero and lived nine years at the University of Hokkaido. A special film was made about this pair of dogs.

Sledges

A variety of sledge designs have been used in the Antarctic, but the 12-foot Nansen sledge has dominated travel, especially with dogs. Sledges have been developed in response to purpose of use, types of surface, and building materials available. The Komatik or Greenland sledge, with its deep, narrow edge-runners and robust structure, has served the Inuit well on the hard coastal sea ice, rocky foreshore, and related conditions in the Arctic, but has not proven so suitable for work in the mountains of the Antarctic or the changing surfaces of the ice shelves and Polar Plateau.

The Nansen sledge, with ski-type runners, copes with these constantly changing surfaces of hard, wind-packed snow and ice, lumpy sastrugi, deep soft snow, or even clear, brittle corrugated blue ice. It must be able to carry a load in excess of 1000 lbs, be able to twist as it moves through the sastrugi, and be able to survive very low temperatures and rapid changes in temperature. The Nansen sledge has a long pedigree and meets all of these demands.

Fridtjof Nansen modeled his sledge on the Greely sledges of the 1880s, aiming for a light but supple model. It is made of a wood that "gives" or "bends," such as ash or hickory. These woods can also withstand the low temperatures and be handled reasonably comfortably. To provide the "twist," the runners, bridges, and longitudinals are assembled with treated hide thronging and flax lashing. These give the required flexibility to the structure.

The runners are flat, 4 inches wide, and curved at both ends. Their surfaces were covered by a resin like Tufnol and more recently by plastics of high molecular weight like polyethylene, with soles 1/4 inch thick. When traversing slopes, metal heels are used. These are placed three quarters of the way towards the rear and dig in 1–4 inches when dropped. Loads are held on laminated beech bridges with 1 1/4-inch-square ash longitudinals. The load sits 12 inches above the surface. The bow at the front is formed by a 9-foot piece of bamboo, bent from runner to runner and called the cowcatcher. It helps to prevent the sledge from overrunning the dogs and braces the front of the sledge.

On a dog sledge, there are handles or a handlebar standing 45 inches high. Pickets, picket hammers, rope thumpers, and a canvas sledge bag hang from this braced structure. A waist-support rope is attached to the handlebar when skiing alongside. A fixed compass is also attached.

For measuring distance traveled, a sledge bicycle wheel is attached with a mileometer gauge. With the help of the compass, a dead-reckoning record can be kept (although this is now almost entirely obsolete with GPS equipment). Traces and tie-lines are nylon rope or lightweight wire. Braking was achieved by using a 4-inch plank of ash with three or four stout studs to dig into the ice. The plank was lashed to the top of the laminated beech bridges. It could be operated by ski or foot. In addition, ropes or chains were fixed under the front of the runners on steep descents.

The Nansen sledge was used by Adrien de Gerlache and his company on the *Belgica* expedition, when they were the first to winter in the Antarctic, as well as by Carsten Borchgrevink and the other members of the *Southern Cross* expedition. It continues to be used as a trailer sledge with motorized ski-doos.

Loads can be heavy, but they need to be evenly distributed. The reinforced plywood boxes, with galvanized edges and weighing 12 lbs, are the favoured way of carrying man and dog food, pots and pans, and the scientific gear. These boxes have wooden blocks on their bottoms and tops to allow them to fit snugly on the sledge and to be stacked. They echo the Venesta boxes of an earlier age. Tents, sea-ice probes, and emergency equipment are lashed down on top of the load. The packing is done in a methodical and similar way on each sledge so everyone knows where equipment is in an emergency or when unpacking at the end of a day's travels. If pups were born on a journey, they frequently were carried on top of the load with the mother running alongside ready to feed them at the halts. On Douglas Mawson's sledge journey with Xavier Mertz and B. E. G. Ninnis, the adult dogs tended to eat newborn pups quickly.

JOHN KILLINGBECK

See also **Adventurers, Modern; Amundsen, Roald; ANARE/Australian Antarctic Division; Antarctic: Definitions and Boundaries; Antarctic Peninsula; Australasian Antarctic Expedition (1911–1914); Belgian Antarctic *(Belgica)* Expedition (1897–1899); Borchgrevink, Carsten E.; British Antarctic *(Nimrod)* Expedition (1907-1909); British Antarctic *(Southern Cross)* Expedition (1898–1900); British Antarctic *(Terra Nova)* Expedition (1910–1913); British Antarctic Survey; British Graham Land Expedition (1934–1937); British National Antarctic *(Discovery)* Expedition (1901–1904); Byrd, Richard E.; Commonwealth Trans-Antarctic Expedition (1955–1958); de Gerlache de Gomery, Baron Adrien; Fuchs, Vivian; Imperial Trans-Antarctic Expedition (1914–1917); Mawson, Douglas; Nansen, Fridtjof; Nordenskjöld, Otto; Norwegian South Polar *(Fram)* Expedition (1910–1912); Ponies and Mules; Protocol on Environmental Protection to the Antarctic Treaty; Scott, Robert Falcon; Shackleton, Ernest; South Pole; Swedish South Polar Expedition (1901–1904); United States (Byrd) Antarctic Expedition (1928–1930)**

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DRAKE PASSAGE, OPENING OF

Drake Passage is the stretch of deep water, some 500 km in width, separating the southern tip of Tierra del Fuego from the northern tip of the Antarctic Peninsula. Today, this passage serves as a "gateway" through which flows the Antarctic Circumpolar Current, the largest ocean current on Earth, with an eastward transport of some 130 million cubic metres of water per second. Opening of the deep-water gateway occurred at some time between 34 and 22 Ma, as South America moved away from Antarctica at a rate of about 20 kilometres per million years. This removed the final barrier to a complete circum-Antarctic pathway for ocean currents, following the slightly earlier creation of another Southern Ocean gateway between Tasmania and East Antarctica. Moreover, this pathway lay within the zone of strong and persistent westerly winds, which began to drive the Antarctic Circumpolar Current, the course of which is closely associated with the position of the Polar Front, the boundary between subantarctic waters in the north, and the cold, polar seas to the south.

Drake Passage opening also had a profound effect on biological evolution, by creating a barrier for land animals migrating across the land bridge between South America and the Antarctic Peninsula. Studies of fossil animals and plants have shown that a number of species passed through a land bridge between the two continents during the warm period that preceded gateway opening, when sea levels were low. Some groups, including a number of small marsupials, were then isolated in Antarctica as a shallow seaway formed, becoming extinct as climate cooled (Reguero et al. 2003).

The Antarctic Circumpolar Current exerts a profound influence on circulation and climate today, and its onset and development are thought to have played an important role in the transition from a warm or "hothouse" Earth in the early Cenozoic (65–50 Ma), to the "icehouse" Earth of more recent times. In particular, one of the most profound climate changes in Earth history occurred 34–33 Ma, at the boundary between the Eocene and Oligocene geological epochs. Records from deep ocean sediments show that, at that time, the Earth experienced a very abrupt cooling, accompanied by the development of extensive ice sheets on the Antarctic continent. This event has long been associated with the initiation of the Antarctic Circumpolar Current as the Southern Ocean gateways finally cleared (Kennett 1977). The essence of this "gateway model" is that the formation of a deep circum-Antarctic ocean, and the consequent onset of the Antarctic Circumpolar Current, effectively cut Antarctica off from warm, southward-flowing currents, resulting in polar cooling and Antarctic glaciation.

The gateway model has recently been questioned, in particular by those using computer models to simulate global oceanic and atmospheric circulation. Results of some recent simulations suggest that opening of Southern Ocean gateways was relatively insignificant, and that the principal driving force for climate change and Antarctic glaciation was declining concentrations of atmospheric greenhouse gases, primarily carbon dioxide. A critical factor in this debate is the relative timing of gateway opening and global cooling. A close correlation between the timing of earliest opening in Drake Passage and abrupt changes in global temperatures would constitute evidence in favour of the gateway model, whereas opening at other times would suggest that gateways were relatively unimportant. Details of the nature and timing of events leading to the establishment of an ocean gateway at Drake Passage are therefore of great importance in understanding the causes of the major global changes that led to the present climate regime.

The sea floor of Drake Passage is formed mainly of oceanic crust, similar to that which lies beneath the major ocean basins, and is covered by a variable thickness of sediments. It was created by the process of *sea floor spreading,* involving the formation of new crust by volcanic and tectonic processes at so-called *spreading centres,* such as the East Pacific Rise and Mid-Atlantic Ridge. Spreading occurs in response to the separation of tectonic plates—the fragments of the outermost 100 to 200-km-thick shell of the Earth that are in constant relative motion—and results in the formation of the deep ocean basins, with typical depths of 2500–5000 m.

In Drake Passage, an extinct spreading centre, known as the West Scotia Ridge, is visible on bathymetric maps as a segmented trough, about 20 km wide, lying at depths 500–1000 m greater than surrounding sea floor, and extending throughout the west Scotia Sea. The period during which the oceanic crust in Drake Passage formed has been dated from the characteristic shapes of marine magnetic anomalies measured by ships as 26–6.5 Ma (Barker and

Burrell 1977). However, anomalies are absent or irregular within about 100 km of the northern and southern margins of Drake Passage, where the oldest crust exists, so that the precise age of the first crust is uncertain. If early rates of opening were similar to those measured for 26-million-year-old crust, then spreading could have begun as early as 34–30 Ma. This accords with an age of c. 31 million years for initial opening of a deep-water pathway suggested on the basis of reconstructions of the past positions of the South America and Antarctica (Lawver and Gahagan 2003).

When continents rift and spreading begins, so-called "passive" continental margins are formed on either flank of the new spreading centre, at the boundary between continental and oceanic crust. These conjugate margins, for example, those off western Africa and eastern South America, can usually be fitted together on a map, so that the sequence of early rifting and separation can be reconstructed. However, while the margin of Tierra del Fuego conforms to this model, there is no obvious southern counterpart to which it may be fitted. This probably results from crustal stretching and deformation within what is now the South Scotia Ridge. This area has been an active plate boundary for at least 6 million years, during which time it has been modified and steepened by faulting.

The onset of deep circumpolar ocean currents need not have been synchronous with the formation of the oldest deep sea floor by spreading at the West Scotia Ridge. It was suggested long ago by Barker and Burrell (1977) that, even though spreading had begun in Drake Passage by 26 Ma, the gateway remained blocked until about 22 Ma by a shallow ridge of continental crust at the Shackleton Fracture Zone. Recent work seems to show that this ridge is actually composed of oceanic rocks and, moreover, may have been uplifted only within the past 6–10 million years (Livermore et al. 2004). It thus appears unlikely that the ridge presented a barrier to an early (i.e., pre-22 Ma) circumpolar current. Other fragments within and around the Scotia Sea, such as Pirie Bank, Bruce Bank, and South Georgia, are more likely to be composed of lighter, continental crust, and hence could have formed a barrier to Antarctic Circumpolar Current flow during the early history of the Drake Passage.

Part of the present controversy surrounding the manner and timing of the Drake Passage opening and the onset of the Antarctic Circumpolar Current stems from uncertainty about the age of the crust beneath the central and southern Scotia Sea. Older models suggest that oceanic crust in the central Scotia Sea, and in the small Protector and Dove basins to the south, was created at about the same time as the West Scotia Sea (i.e., between 23 and 6 Ma). This implies that the continental fragments now separated by these basins were formerly joined, possibly forming an effective barrier to deep-water circulation. An alternative model suggests that these basins may all be older than 31 million years, so that a pathway for the Antarctic Circumpolar Current may have been available soon after spreading commenced at the West Scotia Ridge. A third possibility is that, while the small basins in the southern Scotia Sea opened between 40 and 31 Ma, the central Scotia Sea is younger. In this model, an early "proto-Drake Passage" formed by stretching and rifting of continental crust between 50 and 34 Ma, and was then supplanted by spreading at the West Scotia Ridge. Deep pathways were created and eliminated by the northward movement of South Georgia during this time. All models require that Pirie Bank, Bruce Bank, and South Orkney were part of the former continental connection between South America and Antarctica. If the younger models of central Scotia Sea opening are correct, then South Georgia also formed part of this agglomeration, whereas in the older model, it remained close to the Falkland Plateau throughout and presumably did not present a barrier to deep currents.

Marine geophysical work suggests that a shallow (i.e., less than 1000 m) marine connection was probably established during the Middle/Late Eocene (50–34 Ma), following a major change in the movement of South America relative to Antarctica. Support for the idea of an early opening to shallow depths comes from studies of deep-sea sediments sampled within the international Ocean Drilling Program, which measures various so-called "proxies" for changes in ocean temperature, circulation, and biological productivity. Studies at sites downstream from (i.e., to the east of) Drake Passage, in the South Atlantic and Indian oceans, have shown increases in biological productivity, coupled with a decline in ocean temperature and changes in clay mineralogy, between 40 and 37 Ma, that have been attributed to the opening of Drake Passage to east-flowing currents (Latimer and Filippelli 2002). Likewise, measurements of neodymium isotopes in fossil fish teeth from drill sites in the South Atlantic suggest an influx of Pacific water through Drake Passage at about the same time.

A number of computer simulations of ocean circulation and temperature have been attempted, to assess the effects of gateway opening at Drake Passage on global circulation and climate. The numerical models upon which such simulations are based are highly complex, incorporating global atmosphere, ocean, sea ice, fresh water, and even biological components, but have low spatial resolution (currently 1.25° latitude by 1.25° longitude for the ocean component in the Hadley HadCM3 Model), and so cannot reproduce effects caused by features such as narrow yet deep passages, like those associated with the present Antarctic Circumpolar Current. This may be one reason why recent attempts to model global effects of Drake Passage's opening have produced mixed conclusions. An influential study by DeConto and Pollard (2003) concluded that gateway opening played only a minor role in the abrupt cooling and glaciation event 34–33 Ma, and that the primary cause was declining concentrations of atmospheric greenhouse gases, principally CO_2. Another study by Huber and Sloan (2001), also based on numerical modelling, concluded that changes in heat transport to high latitudes caused by gateway opening were small, and insufficient to bring about Antarctic glaciation. Conversely, other recent simulations (Sijp and England 2004) suggest that Drake Passage's opening, even to shallow depths, could have had a major effect on global ocean circulation, and perhaps on climate too. Resolution of this problem will require much future research, involving deep ocean drilling, to sample and date the crust within Drake Passage, and so develop an evolutionary model for its development as an important ocean gateway.

ROY LIVERMORE

See also **Biogeography; Circumpolar Current, Antarctic; Climate Modelling; Fossils, Plant; Fossils, Vertebrate; Glacial Geology; Islands of the Scotia Ridge, Geology of; Plate Tectonics; Polar Front; Scotia Sea, Bransfield Strait, and Drake Passage, Oceanography of; South Georgia; Southern Ocean; Southern Ocean: Climate Change and Variability; Thermohaline and Wind-Driven Circulations in the Southern Ocean**

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DRY VALLEYS

The conventional image of Antarctica is most probably of a vast empty continental whiteness, almost unrelieved by any of the more familiar features that are associated with the Earth's other landmasses. Although ice dominates the continent, it is a more complex and diverse environment, for Antarctica contains so-called dry areas or oases, atypical regions that are not covered by large ice sheets. Scattered along the coasts and protected by high mountains that block the flow of ice from the interior, these oases, with exposed bedrock, frozen lakes, and flowing waters, have engaged the interests of scientists and explorers alike.

The largest and most widely investigated of the oases is the McMurdo Dry Valleys, a region of some 4800 km^2 between the Ross Sea and the interior of East Antarctica. To enter these parallel valleys—the most prominent of which are the Victoria, the Wright, and the Taylor—is to become part of a strange mosaic of mountain ranges, glaciers, streams, and wind-carved stones.

Exploration of the Dry Valleys began when the members of Robert Falcon Scott's British National

Antarctic Expedition discovered it. Given the harshness of their journey, they marveled at the presence of liquid water and at the sight of exposed earth—the pebbles at their feet and the muddy ground moraines. They also took note of the apparent absence of life. In *Voyage of the Discovery,* Scott wrote: "It is certainly a valley of the dead; even the great glacier which once pushed through it has withered away."

Only several decades separated the journal notes of the *Discovery* expedition from a short article that Barry Lopez wrote for Harper's Magazine in the 1980s. Lopez spoke of the valleys as being "breathtakingly beautiful," of having air of such clarity "that the eye can fasten effortlessly on the details, the sharp break of shadow creases, in distant mountains, making binoculars curiously redundant." The valleys, in his words, were "bold, balanced, serene."

Between the early explorers and the more recent ones, the Dry Valleys have been described largely in the technical literature of biologists, geochemists, glacial geologists, and paleontologists. What has been communicated to the public has been done through the rare television special or through the photographs of Eliot Porter or Craig Potten, whose Dry Valleys are indeed the balanced and serene landscapes about which Lopez wrote.

Nevertheless, the technical summaries of scientific research offer a portrait of the land that is rich and compelling. The valleys are treasure troves of information about ancient landscape processes, ongoing changes in the Earth's climate, and the quality of life *in extremis*. In seemingly lifeless soils, there exists a community of nematodes—tiny worms whose length is measured in millimeters, and yet who are the largest organisms native to the valleys—living among yeasts, bacteria, and filamentous fungi in a matrix of coarse stone and in bitter cold and extreme aridity. Endoliths are another example of life taking anchorage in the harshest desert. These organisms, lichens and bacteria, have colonized the Beacon Sandstone in the high mountains and terraces above the valley floors, growing between the rock crystals just below the surface to be protected from the climatic extremes.

Much has been made by recent researchers of connections and linkages, simple food webs, and survival strategies. In the technical descriptions of the scientific literature, rocks are linked to soils, soils to streams, and streams to lakes. The flows of matter and energy are recorded and modelled, as is the change in temperature over time. And there is a deep concern for the human impact, for the way in which the conduct of science itself may be changing the land, and devaluing its unique features for future generations. Now a rigorous code of conduct for scientific activities is being applied to stop contamination, limit the development of trails, and remove all introduced materials from the valleys.

In the technical scientific literature, a curious and oddly poetic term has often been used to capture the essential mix of elements that interact and give identity to the McMurdo Dry Valleys and that sets them apart from landscapes anywhere else on Earth, and, indeed, from the landscapes of Mars, to which they have often been compared. The word is "mosaic," and it refers to the inlaying of glaciers, ephemeral streams, permanently ice-covered lakes, exposed bedrock, sandy soils, and richly patterned ground, as well as the time and climate that combined to create the valleys.

Glaciers are especially prominent and exotic features of the landscape, flowing down the slopes of the Asgard and Olympus Ranges. Some glaciers, such as those in the Wright Valley—the Denton, the Meserve, the Goodspeed—extend only partway down the mountainside. Others, like the Suess, the Canada, and the Commonwealth, go all the way to the valley floor. The glacier fronts of the Dry Valleys are unusually tall and vertical and, in springtime, thin waterfalls cascade down their faces. In a warming climate many of them appear to be in retreat.

Remarkable, too, are the permanently ice-covered lakes, so oddly out of place in this, the world's driest desert, where annual precipitation is less than 100 mm of water equivalent and where the average temperature is near –20°C. The lakes have long and varied histories and their physics, chemistry, and biology have been the subjects of countless studies over the past 5 decades. Permanent ice covers, some as thick as six meters, float atop liquid water, which may be as deep as 70 m, as in Lake Vanda, or as shallow as 18 m, as in Lake Miers. Past episodes of evaporation have resulted, in some cases, in highly saline brines and in the production of extraordinarily stable, density-stratified water columns. The upper waters of Lake Vanda are cold, fresh, and oxygen rich, while the waters at depth are warm (25°C), salty (three times the salinity of seawater), and anoxic.

The lakes differ in more obvious ways: on Lake Vanda, in Wright Valley, the permanent ice is clear and hard and, across the entire lake, smooth and regular. But this is rare. The surface of Lake Hoare, in Taylor Valley, is rough and deeply undercut and patchy with sand deposits. Divers have found mounds of sand on the lake bottom, and these have apparently been funneled through deep cracks in the surface ice. Lake Bonney is known for the long columnar gas bubbles that are encased in its ice, while Lake Fryxell has mounds of blue-green algae that have become detached from the lake sediments, floated up through the water column, and, gradually, over the course of many years, worked their way to the ice surface. A small water body in Wright Valley, Don Juan Pond, is so saline that it never freezes and so viscous that its waters rarely form ripples.

The lakes do not exist in isolation. They are intimately linked to the glaciers and to valley rocks and soils by the melt water streams. And the streams provide water and nutrients to the few organisms—algae and bacteria, mostly—that can survive in these extreme environments. The ice covers serve as barriers to material inputs from the atmosphere and they prevent direct wind mixing. They also provide extremely useful information about recent climate changes, since ice thickness is related to local meteorological conditions.

Geological history is written clearly in the surrounding rocks. High above are the buff-colored Beacon Sandstones, laid down in the Silurian or Devonian or Jurassic—400 to 200 Ma—when Antarctica was a land of warmth and water and when it was joined to other lands in the great supercontinent of Pangaea, and then Gondwana. It was a time when the land, driven by tectonic plate motion, lay far to the north, long before the onset of the ice sheet. Farther down the slopes of the mountains, the sandstones are cut by the sills and dikes of the Ferrar Dolerites. These dark igneous intrusions appeared in the late Jurassic (170 Ma) and are the signatures of the Earth's mantle and of the welling up of molten rock from beneath the crust. On the valley floor, more recent volcanic deposits have been dated at 4 million years.

By contrast with the mountains, the ice-covered lakes are mere thousands to tens of thousands of years old, and the waters that feed them are days to hours in age.

The wind is also evident in the Dry Valleys. The katabatics from the Plateau develop over the cold ice interior. When pressures fall along the coast of the Ross Sea, air masses rush downward, often at extraordinary speeds. These are desiccating winds, and they are capable of picking up moisture as they move down slope and as they warm under adiabatic compression. Protected from massive glacial incursion by the walls of the Transantarctic Mountains, the McMurdo Dry Valleys are further maintained as arid deserts by these winds. Wind, too, shapes the open land. Throughout the valleys, there are regions of patterned ground where the Earth is tessellated into acres of polygons having diameters as large as thirty meters. When the permafrost slumps into hexagonal or pentagonal rings, the lines that define the perimeters become sites of deposition for windblown sand and sediment. In time, the flat euclidean figure acquires walls, perhaps more than a meter high.

In places, the wind has changed the landscape. Bull Pass, which stretches across the Olympus Range and connects the Wright and Victoria Valleys, offers some of the world's great examples of wind erosion—huge boulders that have been hollowed by salt and moisture, by the freezing and thawing of water, by infinitesimally small accretions acting to pry and loosen the stone. Wright Valley is the site of other wind-shaped stones. The ventifacts—literally made by the wind—lie scattered about in passes and on the valley floor, where they are often subjected to winds of extreme velocity. In 1970, at Vanda Station, winds in excess of 61 km/hr were recorded for a period of 55 days and the maximum wind speed for that winter was nearly 150 km/hr. Carrying an appropriate abrasive material, like sand or ice crystals, winds blowing at these velocities can polish stone to a glassy smoothness in only a few hundred years.

It is still uncertain how the McMurdo Dry Valleys were formed. Early accounts, including those of the British explorers, emphasized the role played by past glaciation events in carving out the three major valley systems. Geologists from the United States and New Zealand, working in the period after the International Geophysical Year (1957–1958), also argued that multiple glaciations in the McMurdo Sound area were largely responsible for shaping the present landscape. More recent interpretations of the geomorphology, however, have also emphasized the role of ancient rivers. The geological history of the McMurdo Dry Valleys remains a subject of great interest and its ongoing study contributes to the developing picture of global change.

In the last two decades, the understanding of the McMurdo Dry Valleys has been greatly expanded by the efforts of scientists working through the Long Term Ecological Research Program in Taylor Valley. This project, sponsored by the US National Science Foundation, has successfully integrated knowledge of ecosystem functions (glaciers, soils, streams, lakes, climate, and weather) through time and has advanced knowledge of nutrient cycling (especially carbon), microbial intervention, and local and regional climate change.

Recognition of the uniqueness and fragility of the McMurdo Dry Valleys has led to efforts to regulate the conduct of scientists and other visitors to the region. An Environmental Code of Conduct now restricts materials brought into the valleys and requires that everything—including human waste—be removed. Among other things, it mandates that oil and fuel spills be reported and remedied; that marked trails be followed where possible; that the number of helicopter landing sites be minimized; and that tourist zones of high aesthetic value be established. These and other provisions of the Code are based on an understanding that the Dry Valley ecosystems operate under severe stress and date back nearly unchanged for thousands and millions of years.

WILLIAM GREEN

See also **Algae; British National Antarctic *(Discovery)* Expedition (1901–1904); Carbon Cycle; Climate Change; Dry Valleys, Biology of; Gondwana; International Geophysical Year; Nematodes; Oases; Oases, Biology of; Plate Tectonics; Ross Sea; Scott, Robert Falcon; Soils; Streams and Lakes; Tourism; Transantarctic Mountains, Geology of; United States: Antarctic Program; Wind**

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DRY VALLEYS, BIOLOGY OF

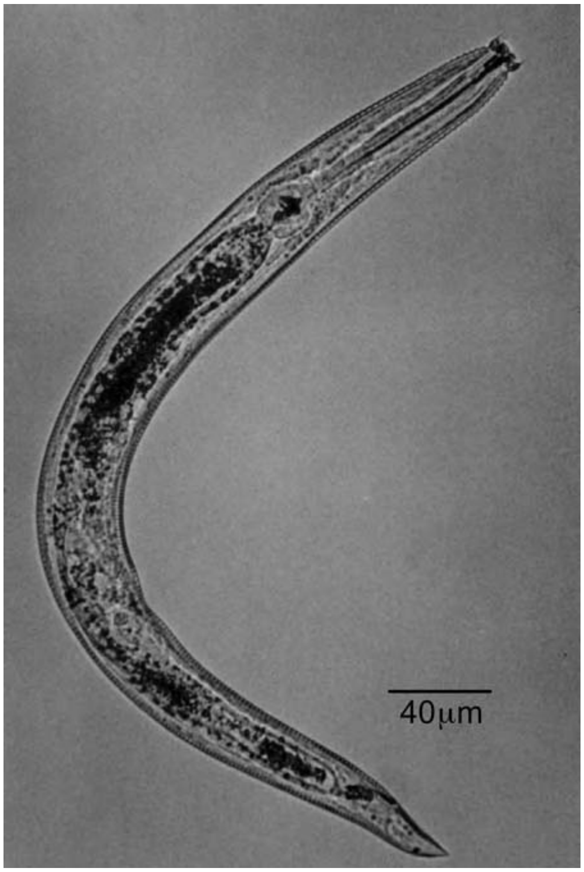
The Dry Valleys are a polar desert with a landscape mosaic of soils, rocks, ephemeral glacial meltstreams, ice-covered lakes, and surrounding glaciers. Although there are no vascular plants or vertebrate animals, they contain a surprising amount of hidden life. This life is mostly microscopic and dependent on minimal moisture from ephemeral glacial meltstreams, permafrost, and snow of less than 4 inches (10 cm) water equivalent per year. The moisture sublimates rapidly, is not readily available in liquid form, and, combined with a mean annual air temperature of –20°C, makes the Dry Valleys one of the most extreme habitats for life.

The landscape is dominated by soils, not ice, that on the surface are patterned into polygon shapes. Soils are poorly developed, coarse in texture (about 98% sand), and, compared to hot deserts, have much lower organic carbon, a more alkaline pH, and higher salinity. Carbon to support the soil food web is from two sources: a legacy of ancient paleo-lakes, and contemporary carbon produced primarily by algae. Organisms are not uniformly distributed across soils in this extreme environment. The more unfavorable soil habitats compose about 40% of the Dry Valleys and are highly saline, more alkaline, lower in carbon and moisture, and inhabited by only a few types of organisms (bacteria, fungi, and/or protozoa). Favorable habitats have the greatest number of taxa (bacteria, fungi, protozoa, nematodes, rotifers, tardigrades, mites, springtails, mosses, lichens, and algae) and occur in soils with higher carbon, higher moisture, and lower salinity, such as those near glacial meltstreams.

Most species occurring in the soils of the Dry Valleys are endemic to the Antarctic, with the exception of protozoa, which are dominated by flagellates and amoebae, with ciliates and testacea rarely found. Fungal-feeding mites and springtails occur under rocks or near meltstreams among mosses, algae, and cyanobacteria. Nematodes exist in about 80% of the favorable soil habitats and have a greater distribution compared to other invertebrates. For example, tardigrades and rotifers occur in less than 20% of Dry Valley soils. The three species of Dry Valley nematodes rarely co-occur, but one and two species communities are frequent in favorable soil habitats. *Scottnema lindsayae,* a nematode that feeds on soil yeast and bacteria, is the most widespread invertebrate in the Dry Valleys, particularly in drier soils, while the two other species, an algal feeder and an omnivore, occur mainly in highly favorable habitats near stream beds or frozen lakes.

Soil is blown onto the surface of lake ice and glaciers, and over time is eventually carried deeper into the glacier or through the ice to the lake bottom, serving as a source of nutrients for the microscopic life. Cryoconite holes on the surface of glaciers are also inhabited by simple communities of organisms, most of which occur elsewhere in the Dry Valleys and include cyanobacteria (e.g., *Chlorococcus, Nostoc*), rotifers *(Philodina gregaria, Cephalodella catellina,)* tardigrades (*Acutuncus antarcticus, Hypsibius* species), and protozoa (ciliates).

The cold, saline, dimly lit, perennially ice-covered lakes house numerous taxa of phytoplankton, algae, bacteria, and fungi. The lakes have alternating layers of benthic (lake bottom) sediment and cyanobacterial mats that are thousands of years old. Floating in water above the mats are protozoa (phytoplankton), including ciliates (e.g., *Oxytrichia, Euplotes, Halteria*) and flagellates (e.g., Chrysomonadida, Volvocida). Protozoan diversity varies between lakes, from approximately forty-seven to seventy-five taxa, and is lower than in temperate lakes. Sediments at lake



Scottnema lindsayae, a nematode that feeds on soil yeast and bacteria, is the most widespread invertebrate and the predominant animal of the Dry Valleys. (Courtesy of D.H. Wall.)

edges support dense populations of algae, bacteria, fungi, protozoa, rotifers, tardigrades, and nematodes *(Plectus)*. Like soils, lakes are influenced by geological history and climate. Lakes with nutrient-rich bottom saline waters have the highest primary production rates. Input of nutrients to lakes varies with the number and length of streams and the presence of nutrient sources amongst them (i.e., algal and bacterial mats and mosses).

Ephemeral streams carry glacial meltwater flow for days to a few weeks during austral summers. Collembola and mites are carried by water as the stream moves across dried soils. The amount of water that flows is highly variable because of the temperature changes affecting the glaciers. Stream channels have predominantly orange microbial mats dominated by several species of *Phormidium* and *Oscillatoria*. On the underside of rocks in the center of the stream, a common but less abundant green algae dominated by *Prasiola* species can occur; in damp areas at the stream margin, one or two black-colored *Nostoc* species are common. A red-colored *Phormidium* algal species occurs in a few streams. Diatom assemblages including *Navicula, Hantzschia,* and *Stauroneis* occur on mobile sediment surfaces. Stream bank vegetation is limited to small patches of mosses. Nematodes occur in stream sediments.

Cryptoendolithic communities composed of several taxa of lichens, algae, fungi, and bacteria live below the surface of translucent rocks (e.g., Beacon quartzite sandstone), where they are protected from the most extreme environmental conditions. As these rocks weather, they provide a source of carbon to soils and serve as propagules for life in other rocks.

Survival mechanisms vary by organism. Algae and cyanobacteria survive periods of desiccation in a freeze-dried state and respond quickly to periodic moisture by beginning photosynthesis. Mites and springtails use supercooling as a mechanism of cold-hardiness. Rotifers, tardigrades, and nematodes avoid desiccation and freezing by entering anhydrobiosis and in this ametabolic state are dispersed by wind across the Dry Valleys. Once favorable environmental conditions return, they revive. Most protozoa are cryophiles (cold lovers).

Emma J. Broos and Diana H. Wall

See also **Algae; Algal Mats; Anhydrobiosis; Benthic Communities in the Southern Ocean; Biodiversity, Terrestrial; Cold Hardiness; Cryoconite Communities; Cryptoendolithic Communities; Decomposition; Desiccation Tolerance; Dry Valleys; Fungi; Lichens; Mosses; Nematodes; Parasitic Insects: Mites and Ticks; Polar Desert; Phytoplankton; Protozoa; Rotifers; Seasonality; Soils; Springtails; Streams and Lakes; Tardigrades**

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DRYGALSKI, ERICH VON

Erich Dagobert von Drygalski was born on February 9, 1865, at Königsberg (today Kaliningrad), and died on January 10, 1949, at Munich.

After studying mathematics, physics, and geography at the universities of Königsberg, Bonn, and Leipzig, Drygalski finished his Ph.D. thesis on the deformation of the geoid during the Ice Age under the well-known geographer Ferdinand Freiherr von Richthofen (1833–1905) at Berlin in 1887. He became the assistant at the Geodetic Institute in Potsdam (1888–1892), before investigating the movement of glaciers and the inland ice during two expeditions to the west coast of Greenland (1891, 1892–1893). During the overwintering there, Drygalski was accompanied by a meteorologist and his old friend and biologist Ernst Vanhöffen.

Through the scientific results of his expeditions, Drygalski passed his habilitation in Berlin in 1898. This paved the way for him to be selected as the leader of the first German Antarctic expedition (1901–1903). Drygalski was very skillful in organizing the comprehensive preparations involving his ship officers and participating scientists, while he entered upon his associate professorship for geography and geophysics in Berlin in 1899. He also was named to lead the physical geography department of the Institute and Museum of Marine Research in Berlin, which had been newly founded by Richthofen. During the Seventh International Geographical Congress in Berlin (1899), Drygalski initiated an international cooperation of simultaneous magnetic and meteorological observations to be carried out by the upcoming British, Scottish, and German Antarctic expeditions.

Throughout his own expedition, Drygalski followed the Humboldtian practice of exploring every aspect of everything new as comprehensively as possible. Unfortunately, his ship was beset by ice close to the Antarctic Circle at 90° E, near where he discovered Kaiser Wilhelm II Land. Although the expedition returned home with a tremendous data set and remarkable collections, his success was overshadowed by Robert Falcon Scott's farthest south of 82°17′ S, which counted much more in the imperial mentality of the time than did any scientific result.

When Richthofen died in 1905, Drygalski temporarily deputized for him, but, due to the lack of popular interest and political support following his Antarctic expedition, he was not named Richthofen's successor. Rather, in 1906 he was given the newly founded chair of the Institute of Geography at Munich. He also presided over the Geographical Society of Munich for 29 years.

In 1910 Drygalski participated in the Zeppelin-Study-Journey to Spitsbergen. During World War I he volunteered to command a company in France and Belgium, but in the final stages of the War he became dean of his faculty (1918), following which he became the rectorate in 1921–1922. As main official advisor for the Emergency Society for German Sciences, Drygalski oversaw the *Meteor* Expedition (1925–1927) and Alfred Wegener's (1880–1930) expeditions to Greenland (1929, 1930–1931). Before his retirement in 1935 he made two study trips to Russia and Siberia (1930, 1931).

Due to political circumstances after World War II, Drygalski returned to his chair at the Institute of Geography for a year. During his entire career, he supported his students, who called him "father," in carrying out their own research. When he died he was recognized as the man who had been the foremost German polar authority during the first half of the twentieth century.

CORNELIA LÜDECKE

See also **British National Antarctic *(Discovery)* Expedition (1901–1904); German South Polar *(Gauss)* Expedition (1901–1903); Neumayer, Georg von**

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DUMONT D'URVILLE, JULES-SÉBASTIEN-CÉSAR

Jules-Sébastien-César Dumont d'Urville, French naval officer and Antarctic explorer, was born May 25, 1790 in Condé-sur-Noireau in Normandy. His family suffered reversals of fortune during the French Revolution. On the death of his father in 1797, the Dumont d'Urville family placed itself under the care of his mother's brother in Caen. Here Jules, a bookish and solitary child, flourished. He studied at the nearby lycée but, missing a place at the Ecole Polytechnique, he joined the navy as an aspirant, or midshipman, in November 1807, serving on a number of vessels, although for much of this time, the fleet was blockaded by the English. In May 1812, after some string-pulling, he was promoted to ensigne de vaisseau. Dumont d'Urville never had much time for the bonhomie of naval life, and during this time he was given the nickname "the owl."

After the fall of Napoleon, his first important cruise was made on the Ville de Marseille to Sicily with the Duc d'Orléans, the future monarch, Louis-Philippe. Over the objections of his mother, on May 1, 1815, he married Adèle-Dorothée Pépin, the daughter of a watchmaker.

Hydrographic duties in the Mediterranean were spent on *Chevrette* (1816–1820). During this time he was instrumental in France's acquisition of the Venus de Milo. Dumont d'Urville's next great opportunity was to serve as second-in-command to Louis-Isidore Duperrey (1786–1865) in an expedition to the Pacific on *Coquille* (1822–1825). He collected three thousand botanical specimens and eleven thousand insects.

On returning to Marseille in March, Dumont d'Urville soon proposed a follow-up expedition, and later that year he was offered command of *Coquille,* now renamed *Astrolabe*. It sailed for the South Seas in April 1826. The high point of this expedition was the confirmation in the Solomon Islands of the loss in 1788 of the mission led by La Pérouse, and the construction there in March 1828 of a modest cenotaph. Its dedication, which Dumont d'Urville was too ill to attend, is depicted in a small painting by Louis-Philippe Crépin (1772–1841) at the National Library of Australia, Canberra.

On returning to France the following year (1829), Dumont d'Urville began the huge task of editing the account of the voyage, published in many volumes between 1830 and 1834 as *Voyage de la corvette* l'Astrolabe. This work established the anthropological distinctions of Polynesia, Micronesia, and Melanesia.

Some years elapsed before another command; the expedition that departed Toulon in September 1837 consisted of two ships, the now-veteran *Astrolabe,* accompanied by the *Zelée*. During this voyage—which took place at the same time as British and American expeditions—Dumont d'Urville made landfall upon Antarctica and in January 1840 claimed Adélie Land, named for his wife. The expedition returned to France in November 1840. Once again he began to compile the account of the expedition. The multi-volumed *Voyage au pôle Sud et dans l' Océanie,* one of the great accounts of exploration of the nineteenth century, was published between 1841 and 1854.

On May 8, 1842, while returning by train from Versailles, Dumont d'Urville and his wife and son Jules died in a derailment at Meudon. They are buried at Montparnasse Cemetery in Paris. A commemorative medal was struck in 1844. Described by a contemporary as "avid for fame," Dumont d'Urville was tireless in the field, and famously indifferent regarding his appearance. His great achievements came, however, at the cost of being considered cold and peevish. His portrait by Jérôme Cartellier (1846) is at the Château de Versailles.

Martin Terry

See also **British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); French Naval (*Astrolabe* and *Zélée*) Expedition (1837–1840); United States Exploring Expedition (1838–1842)**

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DUNDEE WHALING EXPEDITION (1892–1893)

By the 1890s, the Scottish whaling industry was faced with declining stocks in Arctic waters and was looking for new fishing grounds to meet a continuing demand for whale blubber and bone products. The prospect of good fishing in Antarctic waters had been heralded as early as James Clark Ross's expedition in *Erebus* and *Terror* in 1839–1843. Ross had reported sighting the "Greenland," "Right," or Bowhead whale *(Balaena mysticetus),* in and around the Weddell Sea. This was precisely the species sought by northern fleets, the decline of which had made much of the Scottish whaling industry bankrupt. In 1874, a pamphlet was published in Peterhead, *Report on the new whaling grounds of the southern seas,* by the brothers Daniel and John Gray, owners of a well-established whaling fleet. Outside interest for such a venture was also sought in Australia, and an Antarctic exploration committee was formed. Contact was made in Norway with Svend Foyn of Tønsberg and Christen Christensen of Sandefjord—shipbuilder and principal owner of Norway's whaling fleet—as well as with Robert Finnes of Dundee, an important Scottish whaler.

The competition appeared to be fierce: Christensen equipped the Arctic whaler *Jason* for his own expedition and appointed as captain Carl Anton Larsen. They sailed on September 4, 1892. In Scotland, Kinnes assembled a fleet of four ships with 130 crew, at a cost of £28,000. These were sailing ships with auxiliary steam engines: the aptly named *Balaena* was captained by Alexander Fairweather; *Active* by Thomas Robertson, who later would captain the Scottish National Antarctic Expedition ship *Scotia; Diana* by Captain Robert Davidson; and *Polar Star* by Captain James Davidson. The fleet was noteworthy for the signing on as surgeon and naturalist of the young William Speirs Bruce, and his university friend and artist William G. Burn-Murdoch as assistant surgeon. Although Bruce had some medical training, neither was qualified for these posts, and in the event they were fortunately not required to give much medical assistance on the voyage. They hoped, however, to carry out scientific observations and experiments, this being their introduction to oceanographic work in high latitudes.

The fleet sailed from Dundee for the western Weddell Sea on September 7, 1892, and reached their destination December 23. On Boxing Day, December 26, they met with *Jason* to compare observations. However, not a single "Right" whale had been seen and the search was abandoned. In order to recover their substantial costs, they began instead to hunt seals off Joinville Island and northern Trinity Peninsula (the northernmost part of the Antarctic Peninsula), and to fill the ships' holds with sealskins and blubber. It was expected that Bruce and Burn-Murdoch would take part in this slaughter, which both found distasteful. So plentiful were the seals that the fleet sailed toward home waters on February 20, 1893, fully laden. No profits were made, but the costs of the expedition were recovered.

The commercial goals of the expedition had failed, and science had, unfortunately, done little better. Bruce had carried with him instruments loaned by a number of British scientists and by the Royal Geographical Society, and both he and Charles Donald, surgeon on *Active,* carried out meteorological observations. However, the ships' captains had little interest in anything but whaling and sealing, and the scientists found the whole expedition disappointing. However, it gave them a baptism in Antarctic exploration and science, and, for William Speirs Bruce, it formed a major turning point in his life.

Peter Speak

See also **British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); Bruce, William Speirs; Foyn, Svend; Larsen, Carl Anton; Norwegian (Tønsberg) Whaling Expedition (1893–1895); Southern Right Whale; Whales: Overview; Whaling, History of**

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EARTH SYSTEM, ANTARCTICA AS PART OF

Images of Earth from space in the 1970s, and the phenomenon of Southern Hemisphere springtime stratosphere ozone depletion, brought home forcibly the truth that planet Earth is a closed system and that no part can be taken in isolation. Antarctica is an important part of the Earth system, constituting 9.5% of Earth's land surface area. In winter, when sea ice is at its maximum, some 35 million km^2 of the Southern Hemisphere is ice-covered. The Antarctic Circumpolar Current circulates over approximately 22% of Earth's surface, flowing uninterrupted across the southern ends of the three major oceans. The region is an important and very different part of the Earth system and it has been since it was first discovered.

Antarctica is assuming a key global role as an observatory site, and meteorological and seismological data are routinely gathered at many stations; monitoring facilities in support of the Comprehensive Nuclear Test Ban Treaty have been established.

Historical Influence

The earliest ventures to Antarctica were commercial; they were searches for seals to supply the needs of a Northern Hemisphere market. Indeed, this led to the discovery of Antarctica.

Its discovery coincided closely with a time when scientists began to take a holistic view of Earth, through the study of gravity to define the shape of the Earth, and of its magnetic field to define and understand its magnetic characteristics. Henry Foster in *Chanticleer* visited Deception Island in 1829 to take pendulum measurements as part of an international movement; he also took magnetic measurements. In 1839/1840, the expeditions of Charles Wilkes (US) and Jules-Sebastian-Cesar Dumont d'Urville (France) sought in vain the South Magnetic Pole, their efforts thwarted by ice and the continent. In 1840/1841 the Brit James Clark Ross came south in search of this elusive target. He also failed but came close enough to locate it. The Gaussian model of the Earth's magnetic field was vindicated.

Some of the mid-nineteenth-century expeditions had the object of identifying living resources (whales, seals). These were successful in their search, and whaling and sealing industries were of global significance, supplying products, again dominantly for the Northern Hemisphere. From the beginning conservation issues emerged, even among the sealers who were overexploiting the resource.

In the early twentieth century, Antarctica caught the world's imagination through the "Heroic Era" of Roald Amundsen, Robert Falcon Scott, Ernest Shackleton, Douglas Mawson, and others of many nations. Some achievements were overshadowed by the events surrounding the quest for the South Geographic Pole and World War I. The valuable scientific achievements have perhaps been less obvious than the personal.

After World War II, science again began to address global issues, and the International Geophysical Year

(IGY) of 1957–1958 was conceived, the first time that such a program included the Antarctic. It can be viewed as a grandchild of the Wilkes/d'Urville/Ross expeditions 120 years earlier, and forerunner of the Antarctic Treaty.

Recent Recognition

The so-called ozone hole brought home the dangers that face Antarctica and showed that the causes of many problems lay in activities taking place dominantly in the Northern Hemisphere. Within 2 years of publication of the discovery (1985), international diplomatic efforts led to development of the Montreal Convention (signed 1987, in force 1989).

The ozone issue highlighted another feature: the environment is often seen as consisting of the land, ocean, and troposphere. Concerns over ozone highlighted the role of the stratosphere and the attendant solar–terrestrial interaction, which causes, *inter alia,* the northern and southern aurorae.

The Ice and Its Record

The overwhelming feature that distinguishes Antarctica from other parts of the world is its ice, both onshore and offshore. The debate on the environment and global change has drawn out the role of Antarctica as a site for monitoring the health of our Earth's atmosphere and oceans through studies on ice and sediment cores.

The ice sheet contains a record from the past, through the present, into the future. Antarctic ice is an incomparable source of information on baselines against which to monitor change in global environmental parameters, including airborne pollutants; it is far enough removed from sources of pollution that local influences are minimised and only a global signal remains.

The Antarctic ice sheet has a volume of 30×10^6 km^3, enough to raise sea level 60–70 m should it melt. It has a maximum thickness in East Antarctica of almost 4.8 km. In locations where it is thick, elevation is high enough that no melt of the ice occurs, even during summer, when the maximum temperature may be as low as –40°C. Under these circumstances, air trapped between the falling snowflakes and ice grains gets isolated as bubbles. What is sealed off in such bubbles is modern air, but the ice may be 80–250 years old, depending on local conditions and rate of snowfall. The ice has been cored continuously to a depth of more than 3 km, and is over 900,000 years old at Dome C, providing a detailed record of composition of the atmosphere over that time. In the upper part of the section, where annual layers can be identified, changes in composition can be detected seasonally, sometimes even monthly.

The composition of the ice and contained gases can be measured in great detail and tells of variation in global ice volume (and thus sea level), temperature, atmospheric composition, volcanic eruptions, and global wind strength through dust content. Detailed measurements of atmospheric CO_2 over the last 2000 years yield a baseline against which the impact of human activity since the Industrial Revolution can be measured. Volcanic eruptions are recorded as an increase in sulphate in the core leading to an increase in acidity in the ice. Krakatoa (1883), Tambora (1815), and probably El Chichon (1259) show up well and match the annual layer counts. A peak at 1457 coincides with a major explosive eruption at Kuwae in Vanuatu in 1453, identified initially by anthropological research.

Sea Ice and the Influence of the Global Marine Environment

The annual cycle of sea-ice growth and decay causes the formation of cold, dense, high-salinity Antarctic Bottom Water (AABW), which sinks and is a major control on the vertical thermohaline circulation of the world's oceans. This water can be recognised in the North Pacific and Atlantic Oceans. As it sinks down the Antarctic continental margin, it takes with it oxygen to ventilate the deep ocean and provides a basis for life for the organisms living there. Without this oxygen, the deep sea would become stagnant and eventually the life there would die out. This water also acts as a carbon sink by carrying dissolved CO_2 to CO_2-depleted deep-sea water. It also carries atmospheric pollutants; CFCs are a useful marker for water movement because they became available only recently, and are far from completely mixed through the oceans.

The difference between summer and winter distributions of sea ice is a major influence on weather patterns of the Southern Hemisphere through its control on heat exchange between atmosphere and ocean; in winter, the ice insulates the warm ocean (–1.8°C) from the cold atmosphere (–30°C). Southern Hemisphere cold fronts are clearly related to an Antarctic source.

Antarctica in the Long Term

Modern Antarctica is the result of its geological history. Study of the Antarctic provides examples to explain observations made on ancient rocks that formed in continentally glaciated regimes. There are also very important questions, on varying time scales, about rate and amplitude of natural global change that are best studied in the Antarctic.

Antarctica contains examples of some of Earth's oldest lithosphere, almost 4 billion years old in Enderby Land. It tells of conditions and processes at 15- to 35-km depth in an era in planetary development when Earth was without thick modern-style continental crust. As space exploration commences and models of planetary evolution are needed, Antarctica will provide important information for understanding the way this and other planets have evolved.

Earth has evolved through many cycles of continental assembly and reassembly; the latest was formation and breakup of Gondwana. Antarctica has assumed a critical role as a link between former partners in Gondwana and is often referred to as the keystone or centrepiece of Gondwana. It may now best be regarded as the remnant of Gondwana as other continents moved away and recombined in new configurations. The role of Antarctica in Gondwana poses ongoing questions, including the suggestion that much of North America came from the Pacific Ocean between Australia and South America approximately 1 billion years ago—the Rodinia concept. Data gathered in Antarctica were key elements leading to this hypothesis.

The Antarctic Plate is unusual in that the centre is virtually static and surrounded by midocean spreading ridges that are moving away. The exception is the Scotia Arc, where the South Atlantic sea floor is being subduced. The stability goes some way to explain an apparent oddity, that of the lack of earthquakes in Antarctica.

Antarctica is emerging as a source of information on the evolution of life in cold climates. Seymour Island near the Antarctic Peninsula contains a continuous succession of fossiliferous sediments across the Cretaceous/Tertiary boundary (K/T), the time, 65 Ma, of extinction of the dinosaurs due to asteroid or meteor impact in the Gulf of Mexico. This section is valuable because the section is in shallow-water sediments providing insights not available elsewhere.

Thirty million years after the extinction of the dinosaurs, other Gondwana continents had moved far enough away that circumpolar deep-water circulation could commence and the modern ice sheet and global oceanic circulation patterns emerge. This occurred after 99.3% of Earth history had passed.

Fauna and Flora

As Antarctica has evolved, so have its fauna and flora. The current biota is isolated from that of the rest of the world by the Antarctic Polar Frontal Zone (or Antarctic Convergence). This is a clear boundary and only a few whales and flying birds cross it. The isolation of the Antarctic biota is very marked and this has been the case since the Frontal Zone evolved about 20–15 Ma when the oceanographic barriers between Tasmania and Antarctica and South America and Antarctica opened.

This long isolation guaranteed that fauna and flora evolved strategies to survive in an environment different from that elsewhere, and that some of these adaptations will be valuable to humanity in the form of pharmaceuticals and industrial applications. Already whale and fish oils and other products are in use, and antifreeze chemicals identified in the blood of ice fish may pave the way for improved storage of organs for human surgery. These applications will expand as new biochemicals are discovered and developed.

The Antarctic biota became extinct through unusual mechanisms. Most species become extinct as they evolve to new species. Many species and lineages become extinct through mass extinctions such as those 220 and 65 Ma. The Antarctic extinction was different. As circum-Antarctic oceanographic circulation became established, almost all terrestrial vegetation and dependent animals became extinct because the ice sheet grew and pushed them off the land. Until that time, there had been a migration pathway between South America, through Antarctica to Australasia. While the terrestrial biota became extinct, a new biota evolved in the marine environment. It is likely that Antarctica underwent deglaciation and revegetation at times and that a flora typified by the southern beeches *(Nothofagus)* may have lived at 86° S as recently as 3 Ma, raising issues of how readily things can change.

As this extinction occurred, none of the species on land took the opportunity to return to the marine realm as the ancestors of seals, whales, dugongs, and others had done earlier.

Space Links

Part of human nature is to explore; today it is Antarctica; space and the deep sea are emerging. In space, the moon and Mars will be first. The beginnings are much closer to the present day than is the "heroic era." As people explore, the issue of conditions in space becomes focused. Space weather and its prediction are now growing in importance, as is the role of the outer levels of the Earth's atmosphere in the dynamic functioning of Earth and in global change issues. Antarctica already is important in training humans for space travel, in space-related research in medicine, in using the Antarctic as an analogue for space travel, and equipment testing. Antarctic medical records provide some of the best data on how small groups survive long periods in isolated environments.

Antarctica is the best site to conduct optical astronomy and submillimetre infrared astronomy because of the extreme dryness of the atmosphere, lack of pollution, and reliable cold-temperature regime on the high plateau. Concordia was constructed at Dome C in East Antarctica to take advantage of these characteristics.

Antarctica is now the source of 65%–70% of the world's meteorites, and it was one of these meteorites that was claimed in 1996 to preserve evidence of Martian life. Will fragments of other solar system planets and satellites also show up here?

Imaging of the Antarctic from space is now *de rigueur* and saves a great deal of resources.

Bipolar Issues

Both polar regions have phenomena relevant to magnetic poles; they have annual growth and decay of sea ice with consequences for bottom water generation; and they have organisms that are adapted to the cold environment but differ in other ways. There are several groups of microorganisms that have identical species living near both poles but no existence between. What is the mechanism for genetic exchange and similarity between both regions? Perhaps the answer lies in the thermohaline circulation patterns. One region is a continent surrounded by ocean; the other is ocean surrounded by continents. Antarctic research concentrates on those areas that cannot be conducted more cheaply elsewhere. The modern focus on environmental issues in the Antarctic provides an ideal case for cooperation in research around both poles.

The Antarctic as a Commercial Resource

Antarctica has had a commercial value since its discovery, initially for seals and later whales, and now for tourism, krill, and finfish. Increasing population, food, and space requirements and the capacity to produce food ensure that Antarctica will not be quarantined from the needs of the rest of the world.

Fisheries

Antarctic fisheries probably will expand in response to global needs and as fisheries elsewhere decline or come under more stringent control.

Water

As climate changes, conditions for food production in some regions of the world will improve while others will decline. Antarctic ice is already of some interest for water. Any developments in this area will need support from oceanography, glaciology, environment studies, and logistics.

Minerals and Hydrocarbons

Antarctic mineral exploitation is currently far too expensive compared with elsewhere. In addition, the Protocol on Environmental Protection to the Antarctic Treaty (the Madrid Protocol) has put it to one side, and there is growing pressure to move to other forms of energy generation.

Biochemicals

The distinctiveness of the Antarctic biota virtually ensures that biochemically and pharmaceutically useful substances will be found. Already there is considerable interest in compounds from bacteria, in potential sunscreens from algae, and in antifreeze compounds from ice fish. Elsewhere on earth, sponges have proven to be an excellent source of valuable compounds; there is no reason to suspect that those from the Antarctic will be less so.

Tourism

Antarctic tourism is emerging as a popular and diversifying industry. Some ten thousand people see Antarctica from ships during summer and another few hundred see it from overflights. Interest will grow, as will pressure for facilities and for access to new areas.

The Antarctic Treaty

Because of the peculiar features of the Antarctic Treaty, the Convention for the Conservation of Antarctic

Marine Living Resources (CCAMLR) was negotiated after the commencement of the activity that needed to be regulated. The "ecosystem approach" and its attendant "precautionary principle" are important elements and other fisheries management regimes are beginning to incorporate some of these concepts.

The Scientific Committee on Antarctic Research (SCAR) has been successful in stimulating international cooperation and information exchange. The International Arctic Science Council (IASC) has evolved, employing many of the principles and practices developed for SCAR.

Cultural Value

The area is so large and poorly known that a scientist has a greater chance of making a fundamentally new discovery here than anywhere else on Earth.

An identifiably Antarctic culture is emerging and is expressed by an increasing number of works of fiction, of art, and of philately.

As population grows, cities get larger, and individuals get more isolated from their roots, become an older population with time to think and consider their place in the scheme of things, and get hemmed in by more rules and regulations, there will be increasing need to escape. Antarctica will continue to provide a mental release. It is clean, has no indigenous people, is relatively unpolluted, and is inspirational. As more is learned of this region, ideas on the functioning of the Earth's dynamic systems will change.

PATRICK G. QUILTY

See also **Amundsen, Roald; Antarctic Bottom Water; Antarctic Ice Sheet: Definitions and Description; Antarctic Treaty System; Art, Antarctic; Astronomical Observations from Antarctica; Astronomy, Infrared; Astronomy, Submillimeter; Atmospheric Gas Concentrations from Air Bubbles; Aurora; Australasian Antarctic Expedition (1911–1914); Books, Antarctic; British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); British Antarctic *(Nimrod)* Expedition (1907–1909); British Antarctic *(Terra Nova)* Expedition (1910–1913); British National Antarctic *(Discovery)* Expedition (1901–1904); *Chanticleer* Expedition (1828–1831); Circumpolar Current, Antarctic; Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Deception Island; Dumont d'Urville, Jules-Sábastian-Cásar; Fish: Overview; French Naval (*Astrolabe* and *Záláe*) Expedition (1837–1840); Gondwana; Ice Chemistry; International Geophysical Year; Islands of the Scotia Ridge, Geology of; Mawson, Douglas; Meteorites; Norwegian *(Fram)* Expedition (1910–1912); Ozone and the Polar Stratosphere; Philately; Plate Tectonics; Polar Front; Pollution Level Detection from Antarctic Snow and Ice; Protocol on Environmental Protection to the Antarctic Treaty; Rodinia; Ross, James Clark; Scientific Committee on Antarctic Research (SCAR); Scott, Robert Falcon; Sealing, History of; Shackleton, Ernest; South Pole; Thermohaline and Wind-Driven Circulations in the Southern Ocean; Tourism; United States Exploring Expedition (1838–1842); Volcanoes; Whaling, History of; Wilkes, Charles; Zooplankton and Krill**

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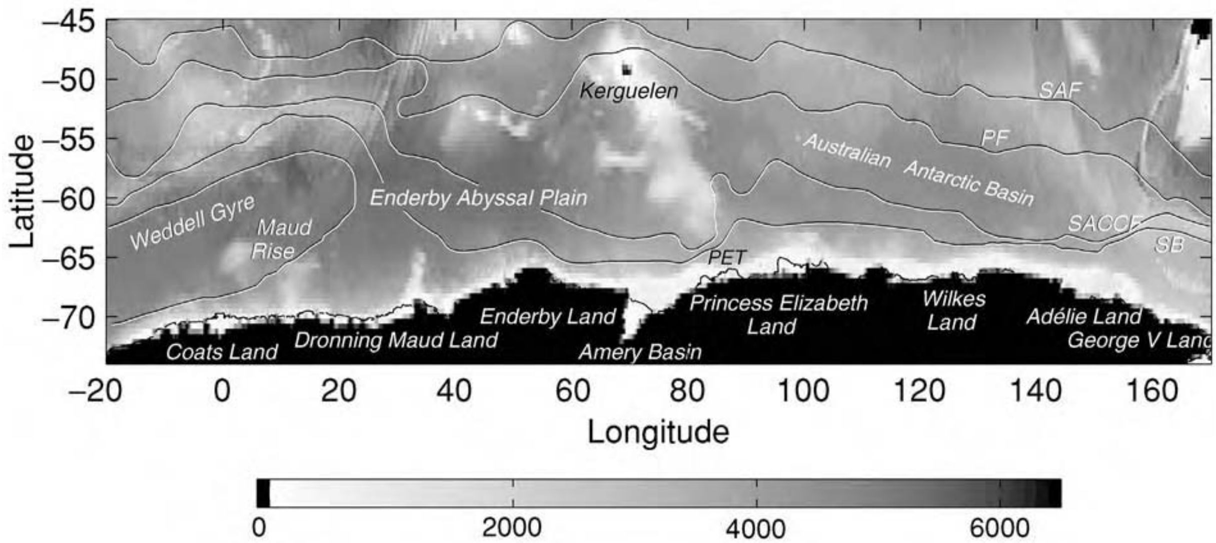
EAST ANTARCTIC CONTINENTAL MARGIN, OCEANOGRAPHY OF

Location and Features

The region that comprises East Antarctica is commonly considered to be that between the Weddell Sea to the west and the Ross Sea to the east (i.e., between around 20° W and 170° E). This encompasses the Antarctic coast and shelf between Coats Land and George V Land, including Enderby Land, Princess Elizabeth Land, and the Amery Basin. The shelf region here differs from those in other sectors of Antarctica in that it is relatively narrow (typically around 50–100 km), especially compared with the much broader shelves in the Weddell and Ross Seas. As for most of the Antarctic, the shelf regions are rather deep compared with ocean shelves around the world, normally a few hundred to several hundreds of metres.

The open ocean adjacent to the East Antarctic margin is dominated by two deep basins, the Weddell-Enderby Basin in the west and the Australian-Antarctic Basin in the east. The Weddell-Enderby



The bathymetry of the ocean adjacent to East Antarctica is shown (depths are in metres). Lines denote the predominant eastward-flowing fronts of the Antarctic Circumpolar Current (ACC); these are (north to south) the Subantarctic Front (SAF), Polar Front (PF), and the Southern ACC Front (SACCF). The Southern Boundary denotes the southern limit of the ACC. The approximate position of the cyclonic (clockwise) Weddell Gyre is also marked. Assorted place names, topographic features, and ocean basins are marked, including the Princess Elizabeth Trough (PET).

Basin is the deeper of the two, with depths in excess of 5000 m. The Australian-Antarctic Basin is, on average, around 4500 m deep. Dividing the two basins is the Kerguelen Plateau, a ridge-like system oriented roughly north–south between 60° and 80° E. Typical depths for the peak of Kerguelen Plateau are between a few hundred metres and a couple of thousand metres, and there is a deep passage separating it from the Antarctic Continent to the south. This is the 200- to 300-km-wide Princess Elizabeth Trough (PET), with a sill depth of 3750 m. The Weddell-Enderby Basin is punctuated by a few rather isolated ridges and seamounts, notably the Conrad Rise (40°–50° E, 55° S), Maud Rise (65° S on the Greenwich Meridian), and the Southwest Indian Ridge, which fringes the basin to the north (between around 55° and 60° S). The Australian-Antarctic Basin has fewer such features, and it is flanked to the north by the Southeast Indian Ridge at around 50°–55° S. This is dissected by a sequence of deep, narrow passages at around 120° E.

At around 70°–80° E lie Prydz Bay and the Amery Basin, containing the Amery Ice Shelf. This is the third-largest embayed ice shelf in Antarctica, and it forms the floating portion of the Lambert Glacier system. Although much smaller than the vast ice shelves in the Weddell and Ross Seas, its presence has potentially significant oceanographic implications (discussed later). While the front of the Amery Ice Shelf accounts for only 2% of the total Antarctic coastline, its catchment area accounts for 16% of the grounded East Antarctic ice sheet. Other, smaller ice shelves fringe the East Antarctic continent, such as the Fimbul Ice Shelf close to the Greenwich Meridian, and the West and Shackleton Ice Shelves in the Australian-Antarctic Sector.

Atmospheric and Cryospheric Forcings

The large-scale barometric pressure field over the ocean in the East Antarctic sector mimics that around Antarctica as a whole. There is a ridge of high pressure in the far north (around 25°–35° S), and a trough just north of the Antarctic continent itself, close to 65° S. This pattern produces strong westerly (eastward-flowing) winds between the ridge and the trough. The circumpolar westerly winds are strongest in the East Antarctic region (around 40°–120° E) and are characterized by frequent storm events, especially in the austral (Antarctic) winter. These winds are, on average, the strongest over the world ocean as a whole. Combined with the absence of land barriers north of Antarctica (i.e., unlimited fetch), this leads to the largest waves in the world during the austral winter. South of the trough around 65° S, the wind direction reverses from westerly to easterly.

The band of strongest winds around Antarctica (around 50° S) coincides with a region of relatively high precipitation. Evaporation is weak throughout the Southern Ocean due to the low air temperatures; thus, precipitation dominates the exchange of freshwater with the atmosphere. Also of great importance are processes associated with the seasonal sea-ice cover in the region. Whilst sea ice in the East Antarctic region melts back almost completely to the continent during summer, the wintertime ice cover extends northward to 60° S or beyond and is generally further north at the western edge of the East Antarctic sector. Maximum ice coverage is normally around September, with the most rapid advance of the ice in May/June. As sea ice forms, salt is rejected, leading to a salinification of the ocean. Conversely, the seasonal melting of sea ice injects a layer of freshwater into the surface ocean.

Not all areas are completely blanketed by sea ice during winter. Some are retained as open-water areas (polynyas), due either to the effect of winds or heat from the ocean. Wind-forced polynyas can form adjacent to the continent, for example, due to winds continuously pushing sea ice away from the coastline. Polynyas can also form over the open ocean; for example, a large polynya occurred in three successive years in the 1970s close to Maud Rise in the Weddell-Enderby region. Regions that are kept clear of ice during the austral winter, despite the extremely low atmospheric temperatures, are free to continuously form more ice as a consequence. Sea-ice formation in general, and in polynyas especially, can be important for dense water formation (explored later).

General Circulation

Originally, the wind pattern previously described led to concepts of a "west wind drift" (eastward-flowing ocean current) associated with the strong circumpolar westerlies over the open Southern Ocean, and an "east wind drift" (westward-flowing current) adjacent to the continent itself. In between these lay the Antarctic Divergence, a region where the Coriolis force (due to the Earth's rotation) tends to push the surface waters apart, leading to upwelling of deeper water from below. These terms are now archaic and the physics they describe is somewhat simplistic, but it is still believed that upwelling of deep waters in the Southern Ocean is important for global ocean circulation. The Antarctic Divergence is notable for being one of the most biologically productive regions in the world's oceans, since the upwelled water is rich in nutrients. This leads to strong production of phytoplankton and zooplankton, which support communities of higher predators such as penguins, seals, and whales.

Modern thinking ascribes the eastward flow in the open Southern Ocean to the Antarctic Circumpolar Current (ACC), a banded feature comprising several fast-flowing current cores, each of which can have surface speeds of several tens of centimeters per second. The fronts are generally termed (north to south) the Subantarctic Front, the Polar Front, and the Southern ACC Front, with the southern boundary marking the poleward limit of the ACC. The fronts are deep-water features, and hence divert north and south of Kerguelen Plateau to negotiate their way around the topography. The forcing for the ACC is at least partially winds, but it has been argued that buoyancy forcing (due to heat and freshwater inputs) is important also. Different estimates for total flow of the ACC in this region exist, but it is normally considered to be in the range of 140–160 Sv, where 1 Sv is 1 million m^3 of water per second.

The western side of East Antarctica contains the easternmost extension of the Weddell Gyre. This cyclonic (clockwise-flowing) gyre fills the Weddell Sea to the west, but also extends out to reach nearly 30° E. The presence of this gyre is the main reason that sea ice extends farther north here in winter then elsewhere along the East Antarctic region.

The term "East Wind Drift" is now rarely seen in oceanographic studies, due in part to a realization that the driving mechanisms for the westward flow south of the ACC can include thermohaline (temperature/salinity) forcing as well as wind stress. Some workers describe an Antarctic coastal current that runs westward around much of the continent, roughly parallel to the Antarctic coastline. This contains water that is colder and fresher than the water from the ACC, which resides close to the shelf break along most of East Antarctica. However, this nomenclature is also not ideal, since the "coastal current" can exist at a great distance from the continent itself in regions where the shelves are broad.

More commonly seen nowadays are descriptions of an Antarctic Slope Front. This is the interface between the cold, fresh water of the Antarctic shelves and the warmer, more saline water derived from the ACC. It often occurs above the upper continental slope, close to the shelf break along the edge of the continent. It is a nearly circumpolar feature that is strongly steered by the bottom topography, and it is characterized by distinct subsurface gradients in temperature (lateral gradients can exceed 3°C in just 25 km). The Slope Front exhibits higher alongshore current speeds than most areas on the adjacent continental shelf, and it has been observed to be a preferred route for icebergs traveling westward along the continental margin.

The Antarctic Slope Front can be a V-shaped double front if the continental shelf is sufficiently wide, but if it is narrow or relatively shallow only a single front (the northern half of the V) is normally present. Where the single front is present, it defines the edge of the cold, low-salinity coastal current extending seaward of the shelf break. Both the single-front and V-shaped frontal configurations can be found adjacent to the East Antarctic continental margin. For example, at around 160° E (off George V Land) and at 80° E (east of the Amery Basin) only single fronts are present, whereas at 145° E (off Adálie Land) and 70° E (close to the Amery Basin) the V-shaped front can be found. It is believed that the V-shaped front often denotes locations where dense waters on the continental shelf can spill off into the deep ocean.

Water Mass Characteristics

The most voluminous water mass in the open ocean close to East Antarctica is Circumpolar Deep Water (CDW). This is a warm, salty, midlevel water mass derived from waters forming in the northern North Atlantic. It is the main water mass of the ACC and is the oceanic source for all water masses that form around Antarctica. The core of the CDW rises up to the south across the ACC, so that despite being very deep at the northern side of the ACC it can impinge on the Antarctic shelf in certain locations. It does this in modified form, since it mixes with shelf and surface waters, which have very different properties.

The water above the CDW between the Polar Front and the Antarctic shelf slope is Antarctic Surface Water. This has changing properties depending on season: sea-ice formation/melting and warming/cooling by the atmosphere are very influential in determining its characteristics. During the austral winter, intense cooling lowers the surface water temperature to its freezing point, and sea-ice formation injects salt into the water. This makes it denser than in summer, and, combined with strong wind-induced mixing action, creates a thick layer (50–150 m) of very cold water at the surface. During the austral spring, the melting of ice freshens the surface of this layer, and the rising air temperatures warm it. This leads to a thin layer of warmer, fresher water at the very surface, with the core of the cold water persisting at depth. This cold core is generally called *winter water*.

Different types of waters exist on the Antarctic continental shelves depending on local processes and mixing with external water masses. These shelf waters are generally very cold (close to the freezing point), but show a wide range of salinities. The high salinity attained by some shelf waters reflects the strong ice production that can exist over the shelf (and hence the large quantities of brine rejected into the ocean). This is especially true for regions with polynyas, which can continue forming ice throughout the austral winter. Normally, it is broad shelf regions with topographic obstacles (such as the western Weddell Sea) that show the highest prevalence of high-salinity shelf water, although it can form in East Antarctica also, including close to the Adálie Coast.

As well as high- and low-salinity shelf waters, a third type of shelf water exists, one that is formed by the interaction of seawater with a floating ice shelf. In East Antarctica, the Amery Ice Shelf near 70° E is the main location for the formation of this Ice Shelf Water (ISW). This forms when dense water at the bottom of the continental shelf flows into the cavity beneath the ice shelf. The Lambert Glacier grounding point is almost 2500 m below sea level, and the huge pressure exerted on the water by the weight above it means that the freezing point is lowered from around –1.85°C to well below –2°C. As the inflowing seawater comes into contact with the glacier, it melts some of the glacial ice, thus becoming cooler and fresher. However, the decreased freezing point due to the great pressure means that the water can get significantly colder before freezing. Upon exiting the ice shelf cavity, the ISW is thus fresher than the inflowing water was, but is also cooler and is only kept liquid by the pressure it is under. Some of the seawater does freeze onto the underside of the ice shelf, forming layers of "marine ice." This is the reason that icebergs that calve from the Amery Ice Shelf are often reported to have an emerald-green appearance. Many of the green icebergs observed in the Weddell Sea are believed to have originated from the Amery Ice Shelf.

Bottom Water Formation in East Antarctica

The shelf waters close to Antarctica are globally important since they are crucial to the formation of *Antarctic Bottom Water* (AABW). This resides below the CDW in the open Southern Ocean and spreads out as the abyssal layer of the global ocean circulation. AABW is slightly fresher than CDW, but it is also much colder, and hence is dense enough to sit beneath CDW in a stable water column. AABW forms close to the Antarctic continent through the mixing of dense shelf waters (including possibly ISW) with modified forms of CDW. The mixing required can be facilitated by high levels of tidal energy near the shelf break. The sinking of dense waters along the Slope Front near the shelf break can contribute recently formed waters to the CDW layer as well as the AABW layer.

Until recently, it was believed that AABW production was restricted predominantly to the Weddell and Ross Seas. However, the relative prominence of East Antarctica in this role has been progressively more recognized in recent studies. The Wilkes-Adálie Land coast (between around 138° and 158° E) has received much interest in this context. That AABW forms here is in some ways surprising, since the region's shelf is comparatively narrow, contains no topographic barriers such as would help the pooling of brine-enriched shelf waters, and features no significant ice shelves that would promote the formation of large amounts of ISW. It does, however, show distinctive shelf waters in a depression between 142.5° and 145.5° E that have their salinity increased by intrusions of modified CDW. An unusually large and persistent coastal polynya also adds to the salinity enrichment of the shelf waters here. Mixing of these waters with the CDW that impinges on the shelf leads to the formation of AABW, dense plumes of which lie over the continental slope. AABW that forms in the Ross Sea further east can also enter the Australian-Antarctic Basin; however, the locally formed variety is distinctive based on its colder and fresher properties. These distinctive characteristics have enabled quantification of importance of the AABW formed in the southeast Indian Ocean. It has been suggested that this region contributes up to one-quarter of the total global ocean volume colder than 0°C.

The AABW in the Australian-Antarctic Basin can escape northward through gaps in the Southeast Indian Ridge or can flow westward through the PET into the Weddell-Enderby Basin. Much of the AABW that enters the East Antarctic region from the Weddell Sea either recirculates in the Weddell Gyre or escapes to the northeast through gaps between Kerguelen and other nearby islands. Small amounts of AABW formed in the Weddell Sea are believed to be able to enter the Australian-Antarctic Basin by being advected south of Kerguelen Plateau in the ACC, but this is unlikely to be volumetrically very significant.

In addition to the Adálie Coast area, the region of Prydz Bay and the Amery Ice Shelf has also received interest as a possible source of AABW. Whilst the issue is still somewhat unresolved, there are some strong suggestions of AABW formation in the vicinity. For example, high concentrations of dissolved chlorofluorocarbons (CFCs) along the continental slope further west of the Amery Basin have been interpreted to suggest a quite local source of AABW, and observations of high salinity shelf waters close to the shelf break here have lent further evidence.

It is important to note that the properties of AABW, and indeed other water masses in the East Antarctic region, will not be constant with time. Whilst this region is beset by a paucity of data from earlier periods, it has already been noted that the bottom water in the Australian-Antarctic Basin has shown a very pronounced freshening since 1994. Further, consideration of water mass properties over the continental rise between 140° and 150° E has shown a very significant drift toward lower salinity and temperature over the past 50 years. It is likely that the AABW derived from the Ross Sea in this region has also freshened over this same period, since the shelf waters there have been observed to have freshened dramatically. The causes of this large-amplitude freshening over this region of the Southern Ocean are not yet known, but they could include changes in winds and precipitation, long-period variability in sea-ice formation, and an acceleration of melting of glacial ice from Antarctica. Given the potential consequences for the global ocean, it is important that this issue be further explored.

MIKE MEREDITH

See also **Antarctic Bottom Water; Antarctic Divergence; Antarctic Surface Water; Circumpolar Current, Antarctic; Circumpolar Deep Water; Coastal Ocean Currents; Continental Shelves and Slopes; Ice Shelves; Polar Front; Polynyas and Leads in the Southern Ocean; Southern Ocean: Fronts and Frontal Zones; Southern Ocean: Vertical Structure**

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EAST ANTARCTIC SHIELD

Shields and Cratons

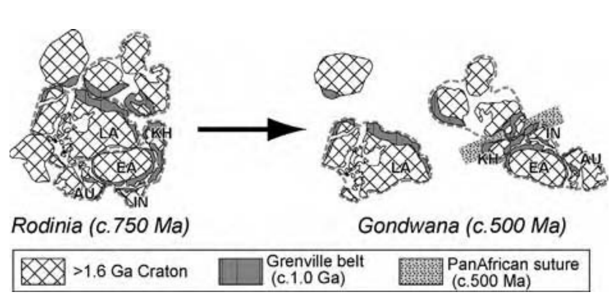
Most of the crust of the world's seven continents is composed of two types of rock: shields and platforms. In the 4.6-billion-year-long history of the Earth, the period before 570 Ma is called the Precambrian age. A shield is a land mass where ancient Precambrian rocks are exposed on the Earth's surface, whereas a platform is a part of a continent where younger sedimentary layers cover a basement of Precambrian rock. Shields and platforms are the two main components of cratons, which are the parts of a continent that have been tectonically stable since Precambrian times. Cratons are typically joined together by orogenic ("mountain-building") belts, where moving continental plates have collided. Many cratons have been stable since Archean times, in the early part of the Earth's history. Such old and stable continental pieces have been weathered and eroded for enormous periods of time. As erosion carries away the weight of the top of a craton, the continental crust slowly rises, exposing plutonic and metamorphic rocks that formed deep below the surface. This erosion produces a landscape that curves gently from the center to the margins of the craton, like the curved shields of the warriors of ancient Europe; hence the term "shield" (the phrase was first coined in 1888 by Eduard Suess [1831–1914] when he described the Canadian Shield). The heart of the Canadian Shield, in the area around Lake Superior, is a collage of Archean cratonic pieces, Proterozoic orogenic belts, intracratonic igneous rocks, and sedimentary layers. Most of Antarctica is composed of the East Antarctic Shield, which consists of a variety of Precambrian terranes, and although it is mostly hidden under ice, there is no reason to believe it is very much different from the other Precambrian shields of the world.

Subglacial bed topographic map of Antarctica. Numbers (1000, 0, –1000) indicate bed rock altitude contours (m). (Drawn based on the data set downloaded from BEDMAP [http://www.antarctica.ac.uk/aedc/bedmap/].)

Continental Drift and East Antarctica

More than 30 years before the discovery of plate tectonics, a theory of drifting continents was proposed by Alfred L. Wegener (1880–1930), a German climatologist. Using geological and geophysical evidence, he suggested that continental blocks now separated by oceans had once been joined as one great supercontinent.

Wegener thought the resemblance of the Atlantic coast lines of Africa and South America showed that the two continents were once contiguous. From the similarities between distributions of plant fossils that had grown in similar climatic conditions (Gondwana Flora), sediments deposited by Paleozoic glaciers,

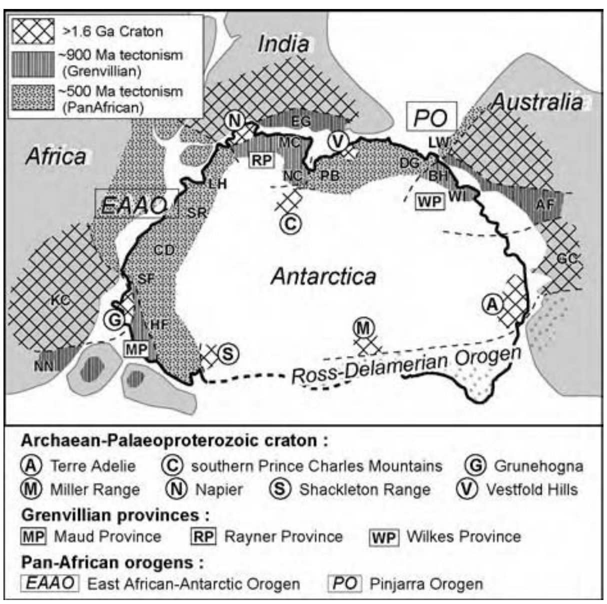


Traditional model of Rodinia and Gondwana supercontinents. EA: East Antarctica (after Hoffman, 1991), IN: India, AU: Australia, KH: Kalahari (southern Africa), LA: Laurentia (northern America).

fossils that had lived on land or in fresh water, and continuity of geology between the two facing continents, Wegener proposed that a supercontinent existed from the late Paleozoic to the Mesozoic: Gondwana or Pangea, in which Laurasia is included. Wegner could not understand, however, what forces had driven the movement of continents, and his hypothesis had little impact until the plate tectonics theory was developed decades later.

In Wegener's time, scientific understanding of Antarctica was very limited, but many plant fossils of Gondwana Flora were found in the Beacon Sandstone beds in the Transantarctic Mountains. Samples from the British Antarctic *(Terra Nova)* expedition (1910–1913) were later found to contain leaves and stems of *Glossopteris,* an extinct tree found in continents that were part of Gondwana. Thus it was proven that Antarctica was a part of Gondwana in the late Paleozoic to early Mesozoic (about 200 Ma).

A South African geologist, Alexander du Toit (1937), noted that East Antarctica was a key piece of the Gondwana supercontinent, because it was surrounded by continents such as South America, Africa, Australia, and India until about 180 Ma. In addition, East Antarctica is also a key component of an earlier Neoproterozoic supercontinent, known as



East Antarctica and neighboring continents in Gondwana reconstruction. AF: Albany-Fraser Range, BH: Bunger Hills, CD: central Dronning Maud Land, DG: Denman Glacier, EG: Eastern Ghats, GC: Gawler Craton, HF: Heimfrontfjerra, KC: Kaapvaal Craton, LH: Lützow-Holm Bay, LW: Leeuwin Complex, MC: Mawson Coast, NC: northern Prince Charles Mountains, NN: Namaqua-Natal, PB: Prytz Bay, SF: H.U.Sverdrupfjella, SR: Sør Rondane Mountains, WI: Windmill Island.

Rodinia. In the following description, the general features of the East Antarctic Shield are discussed in terms of the history of crustal evolution.

East Antarctic Shield

Antarctica is divided into two geographic domains by the Transantarctic Mountains, a 3500-km-long and 4500-m-high mountain range. West Antarctica occupies the Pacific Ocean side, and East Antarctica is on the side of the Indian and South Atlantic Oceans.

West Antarctica is a complex assemblage of accreted terrenes, composed mainly of four continental blocks that have moved against each other and toward East Antarctica during the Phanerozoic (the part of the earth's history after 570 Ma).

The crustal structure of East Antarctica is less well understood. Geological information on the basement beneath the ice sheet, which covers more than 98% of East Antarctica, can only be obtained by indirect means of geophysical investigation such as seismic, magnetic, and gravimetric surveys, along with radio-echo sounding for ice-thickness measurement. An ice-thickness and sub-ice (or subglacial) topographic model of the Antarctic was compiled by an international project called BEDMAP (bed topography of the Antarctic).

The most prominent sub-ice topographic features in East Antarctica are the Gamburtsev Subglacial Mountains, which reach 2000 m above sea level below Dome A, the highest part of the East Antarctic ice sheet. The Lambert Glacier, which is the largest ice stream in the world, flows from the Gamburtsev Subglacial Mountains along a depression northwards to Prydz Bay. The ice depression is believed to overlie the Lambert Graben, a huge rift in the underlying continent that extends at least 700 km inland from the Antarctic coast. In the northern Prince Charles Mountains, the fault system of the Lambert Graben disrupts the Permo-Triassic Amery Group and juxtaposes it against Proterozoic basement.

Also prominent are two large subglacial basins in Wilkes Land, named the Aurora and Wilkes basins. The Wilkes Subglacial basin parallels the Transantarctic Mountains on the polar side and is thought to contain one to several vertical kilometers of sediment infill.

In contrast to the interior of the continent, rock exposures in the coastal regions and mountain ranges are generally glaciated pavements and large cliff sections, suitable for direct geological observations.

East Antarctica was once regarded as a single huge Precambrian craton, but intensive investigations since the 1960s and, in particular, recent advances in geochronological techniques have made it possible to reveal the complex history of the Precambrian East Antarctic Shield. Studies on Precambrian geology are based on the correlation of the field relationships of rock types, chemical compositions, and ages of rocks and constituent minerals. The ages of prefossil Precambrian rocks can only be determined by isotopic dating techniques. Combinations of rubidium–strontium, samarium–neodymium, potassium–argon, argon–argon, and uranium–lead geochronology have been most popular and, in particular, the recent development of uranium–lead geochronology by analysis of zircon with ion-microprobe has revealed much about the complex tectonic history of the East Antarctic Shield, because mineral growth is accelerated and controlled by the heating that accompanies tectonic events. In this article, age determinations are mostly derived from ion-microprobe data.

The complex history of the East Antarctic Shield includes three major stages of tectonothermal activity: (1) development and stabilization of various Archean to Paleoproterozoic cratons before 1600 Ma; (2) development of a late Mesoproterozoic orogen (1300–900 Ma); and (3) late Neoproterozoic to early Paleozoic (550–450 Ma) tectonism. The stabilization of Archean to Paleoproterozoic cratons may be subdivided into two stages: Late Archean to earliest Proterozoic (i.e., between 2840 and 2480 Ma) and Paleoproterozoic (2200 to 1700 Ma). The 1300–900-Ma orogeny is contemporaneous with the Grenville orogeny in North America and the Kibaran orogeny in Africa, whereas the late Neoproterozoic to early Paleozoic (550–450 Ma) event is coeval with the Ross Orogeny in the present-day Transantarctic Mountains and the Pan-African Orogeny (East African Orogeny) in east Africa.

In this article, we identify the late Mesoproterozoic to early Neoproterozoic orogeny as the "Grenville-age orogeny" and the late Neoproterozoic to early Paleozoic (550–450 Ma) tectonism as the "Pan-African event." The geographic directions in this article refer to the present-day positions of continents.

Since the East Antarctic Shield has a long history, the basement rocks of many areas have been repeatedly reworked by tectonism. The effect of the Pan-African event, which is the youngest regional tectonothermal event in East Antarctica, differs from place to place. Hence, in this article, the regional geology is described in key areas that are relatively well described in terms of tectonic evolution. These areas are grouped into (1) Archean and Paleoproterozoic cratons and (2) Grenville-age orogenic terranes, each of which may or may not be reworked by Pan-African tectonism. Then the discussion will be focused on the Pan-African event.

Archean and Paleoproterozoic Cratons

Archean cratons are mainly composed of metamorphosed igneous rocks (orthogneisses) containing zircons older than 2.5 Ga. These orthogneisses have been reported from coastal regions (Shackleton Range of Coats Land, Western Dronning Maud Land, Enderby Land, Princess Elizabeth Land, Queen Mary Land, and King George V Land) and inland regions (Southern Prince Charles Mountains and the Miller Range of the central Transantarctic Mountains). Many of the Archean cratons were repeatedly reworked into the Paleoproterozoic. The Archean–Paleoproterozoic cratons vary widely in size and age, reflecting the long and complex history of the early Earth.

The Shackleton Range of Coats Land consists of east–west-aligned mountain chains. It was once considered to be a part of the Ross Orogenic Belt of the Transantarctic Mountains; the structural trend of the range, however, is not consistent with that of the Transantarctic Mountains. It is now regarded to be a part of the East Antarctic Shield. The basement of the mountains is composed mainly of amphibolite facies (medium-grade metamorphic) rocks. The Shackleton Range can be divided into a northern block that is composed of reworked Archean–Paleoproterozoic cratonic fragments, along with ophiolite complexes (relics of ocean floor rocks) and low-grade metasedimentary rocks with Cambrian *Archaeocyathus* fossils, and a southern block that is entirely composed of Archean-Paleoproterozoic craton. The northern block of the range has been thrust over the southern block by Pan-African thrust faults, due to the collision between the East Antarctic Craton and Kalahari Craton.

No Archean craton has been reported from Dronning Maud Land, except for Archean granite of 3000 Ma exposed at Annandagstoppane in western Dronning Maud Land. This granite has been called the Grunehogna Craton and is regarded as a portion of the Kaapvaal Craton (the southern part of Kalahari Craton), which was detached from South Africa during the breakup of Gondwana.

In the 1970s, Russian geologists reported lead–lead ages of about 4.0 Ga from the Fyfe Hills in Enderby Land. The finding of such ancient crust generated intense interest in the metamorphic and igneous rocks of Enderby Land that form the Napier Complex. The oldest components of zircon in orthogneiss at Mount Sones crystallized at 3930 ± 10 Ma. This is the second-oldest age recorded for an *in situ* terrestrial rock and the oldest age in Antarctica, but later more precise studies showed the main igneous activity occurred at about 3800 Ma. The Archean orthogneisses are typically potassium-poor granitoids of the tonalite–trondhjemite–granodiorite (TTG) series, which plays an important role in the formation of new continental crust.

Several subsequent episodes of Archean thermal activity were identified via ion-microprobe dating of zircon, at c. 3300 Ma, c. 3000 Ma, c. 2900 Ma, and c. 2500 Ma. However, these events have not always occurred everywhere in the complex. The oldest crust is restricted around Mount Sones in the central part of the complex, but c. 2500 Ma a thermal event occurred throughout the complex.

The Napier Complex is also characterized by metamorphism at more than 1000°C (ultra-high-temperature (UHT) metamorphism). The age of UHT metamorphism is controversial because of the long complex metamorphic history. The source of such extreme heat is also uncertain, with most models invoking the deep-level emplacement of large volumes of magma into double-thickened continental crust.

The Archean-Paleoproterozoic cratons in the coastal regions of East Antarctica are comparable with those of adjacent Gondwana fragments. The Napier Complex would have adjoined the cratons of the Indian peninsula prior to the breakup of Gondwana.

In the southern Prince Charles Mountains, Archean granitic gneisses are overlain by Late Archean metasediments. Some were affected by Mesoproterozoic to Neoproterozoic medium-grade metamorphism, whereas greenschist-facies (low metamorphic grade) phyllites and banded iron formations are Late Archean to Paleoproterozoic in age. Ion-microprobe ages for zircon from the granitic gneisses are 3170–3000 Ma, and later undeformed pegmatites intruded at c. 2640 Ma.

In the Prydz Bay area, Archean high-grade metamorphic rocks crop out in the Rauer Islands and Vestfold Hills. These localities are separated by a glacier only 12 km wide, but the ages of the Rauer Group (2800 Ma and partly 3270 Ma) gneisses are significantly older than those of the Vestfold Hills (c. 2500 Ma).

In Queen Mary Land, there are at least three outcrops of Archean high-grade orthogneiss around the Denman Glacier region, with ages between 3000 Ma and 2640 Ma.

East of King George V Land, craton areas used to be regarded as mainly composed of Paleoproterozoic high-grade gneisses. Ion-microprobe zircon and monazite ages from paragneisses (medium- to high-grade metamorphic rocks of sedimentary origin) place the high-grade metamorphic event at c. 2420–2440 Ma, followed by a 1710-Ma overprint and granite magmatism at c. 2520–2560 Ma. Paleoproterozoic rocks on the coast of Terre Adelie and King George V Land are similar in lithology and age to those of the Gawler Craton in southern Australia. A large continental block consisting of these cratons together with the inferred sub-ice cratonic crust has been proposed and named the Mawson Continent after the Antarctic explorer and geologist Douglas Mawson.

In the Miller Range of the Transantarctic Mountains, the oldest gneisses represent Archean magmatic crust generated from juvenile mantle melts between 3.15 and 3.00 Ga, indicating that the East Antarctic Shield extends to the central Transantarctic Mountains. Later episodes of high-temperature metamorphism and magmatism occurred at c. 2.5 Ga and c. 1.7 Ga. The c.-1.7-Ga event is correlated with similar ages in Terre Adelie and King George V Land and the basement of the Miller Range is potentially a part of the Mawson Continent. Furthermore, inland cratons such as the southern Prince Charles Mountains and the Shackleton Range have been also correlated with the Mawson Continent, although the age data are limited. If all these areas were unified, combined with the Gawler Craton, the Mawson Continent represents a huge Late Archean to Paleoproterozoic continental province.

Late-Proterozoic to Early-Paleozoic Evolution of the East Antarctic Shield

The traditional model of Late-Proterozoic to early-Paleozoic evolution of the East Antarctic Shield has been described in a framework of amalgamation and dispersion of the Rodinia Supercontinent, followed by the collision of East and West Gondwana to form the Gondwana Supercontinent (e.g., Hoffman 1991; Dalziel 1992).

It has been proposed that a continuous Grenville-age (c.1300–900 Ma) mobile belt surrounds East Antarctica from Coats Land to Wilkes Land, through Dronning Maud Land, Kemp Land, the northern Prince Charles Mountains, Princess Elizabeth Land, and Queen Mary Land.

This belt was called the Circum-East Antarctic Mobile Belt (CEAMB) or the Wegener-Mawson Mobile Belt. The CEAMB in East Antarctica was considered to extend into Grenville-age mobile belts in North America, Africa, India, and Australia, resulting in the amalgamation of the early Neoproterozoic supercontinent Rodinia (see Hoffman 1991).

According to this model, the breakup of Rodinia occurred when the North American block split away from the continental blocks of East Antarctica, Australia, Peninsular India, Madagascar, and South Africa, which are collectively known as East Gondwana. East Gondwana subsequently collided with the West Africa, Congo, and Kalahali cratons, which form West Gondwana. The collision of East and West Gondwana is known as the Pan-African Orogeny or East African Orogeny. The suture of the collision is well documented in northeastern Africa to Mozambique, whereas the southern continuation of the suture in southeast Africa and East Antarctica has been more controversial, although Pan-African metamorphism and magmatic activity has been widely recognized in East Antarctica. The accumulation of zircon uranium–lead age data has revealed that the CEAMB was not continuous but separated into three major provinces, Maud, Rayner, and Wilkes, which are separated by two regions of Pan-African high-grade metamorphism and tectonism in Dronning Maud Land and the Prydz Bay-Denman Glacier region. Fitzsimons (2000a) also pointed out that the three Grenville-age provinces have different time spans: 1090–1030 Ma, 990–900 Ma, and 1330–1130 Ma, respectively.

Maud Province and Pan-African Overprint

The rocks in Dronning Maud Land (DML) are exposed in east–west-trending mountain ranges along the boundary between the plateau and shelf ice sheets. Maud Province, in the strict sense, was defined as a Grenville-age mobile belt in the western DML, which is a part of the Namaqua-Natal-Maud Belt (Jacobs et al. 2003). However, some authors regard areas of central and east DML that show intense Pan-African reworking as parts of the Maud Belt (see Frimmel 2004).

The lithology of the basement rocks of this belt is rather similar between Heimfontfjella in the western DML (c. 10° W) and the Sør Rondane Mountains in the east (c. 25° E). It is predominantly composed of multiply deformed medium- to high-grade metamorphic volcanic rocks and subordinate metasedimentary rocks, intruded by various, mainly granitic, plutonic rocks.

On the basis of chemical composition, the igneous protoliths from these areas have been interpreted as deriving largely from magmas in oceanic, island-arc, accretional complex and continental margin island arcs, analogous to modern plate-tectonic settings. Combined with ion-microprobe zircon ages and samarium–neodymium model ages, the basement of the DML is interpreted to be juvenile Mesoproterozoic island-arc material accreted to the Gurunehogna Craton and possibly an as-yet-unidentified older continent that existed further south in the DML.

In the western DML, the degree of Pan-African metamorphism decreases towards the west. The Heimfontfjella region is divided by the Heimfront Shear Zone. Northwest of the shear zone, the Pan-African overprint is limited to low-grade (greenschist facies) metamorphism and the intrusion of granites and pegmatite dykes, whereas the eastern zone records intense polyphase deformation and high-grade metamorphism. Thus the Heimfront Shear Zone has been identified as a major zone along the western front of the Pan-African Orogen in Antarctica. Jacobs et al. (2003) propose that the suture of collision between East and West Gondwana extends to Dronning Maud Land, and call the orogenic belt the East African-Antarctic Orogen (EAAO).

Rayner Province and Wilkes Province

The late Mesoproterozoic Rayner Complex in Enderby Land had originally been interpreted as a reworked part of the Archean Napier Complex. However, later geochronological studies showed that the Rayner Complex is composed of 990–900 Ma high-grade metamorphic rocks of pre-Grenvillian felsic plutonic rocks and subordinate paragneisses showing Mesoproterozoic depositional age. Similar terranes continue along the Mawson Coast of Kemp Land and further to the northern Prince Charles Mountains, and rocks in the Eastern Ghats Province of India show similar ages. Together these areas are called the Rayner Province and are regarded as a Grenville-age mobile belt that records the collision of the Indian shield with a central Antarctic craton exposed in the southern Prince Charles Mountains.

The Wilkes Province is the easternmost outcrop of Grenville-age mobile belt in East Antarctica, and lies along the coast in the Windmill Islands and Bunger Hills of Wilkes Land. Two episodes of high-grade metamorphism at 1330–1280 Ma and 1200–1130 Ma have been correlated with the Albany-Fraser province in Australia.

Pan-African Tectonism in the East Antarctic Shield

The EAAO is a Himalayan-type orogenic belt that extends over 8000 km. The western orogenic front of the EAAO is exposed as the Heimfront Shear Zone in Heimfrontfjella in western DML. Some geologists interpreted the Maud province, together with the Falkland Islands and the shear zone–bound Ellsworth-Haag Block, as laterally slipped (escaped) older crustal blocks that were not subjected to tectonothermal reworking c. 500 Ma. Similar escape-tectonic processes are happening today to crustal blocks in Southeast Asia that represent the southeastern extension of the Himalaya Orogen.

In Coats Land, there are few outcrops exposed. Only airborne geomagnetic mapping data suggest that the area, the Coats Land Block, is similar to the east of the Heimfront Shear Zone, indicating the zone of the EAAO. In the Shackleton Range, located in the south of the Coats Land Block, there are slices of Pan-African thrusts overriding the southern craton. Many authors suggest a Pan-African suture is involved in the Shackleton Range.

In the central and east DML, evidence of two distinct major orogenic events has been distinguished: the high-grade metamorphic Grenville event and the high- to medium-grade Pan-African event. Integration of the isotopic ages revealed that the Pan-African event in the DML is more complicated and two stages of metamorphic events succeeded by the post-tectonic granite activity have been recognized in several areas in the DML, although the time span is different from place to place. In H.U. Sverdrupfjella, which is adjacent to the Grunehogna Craton, an earlier Pan-African event (c. 565 Ma) is high-pressure-type metamorphism, suggesting the deeply subducted lithosphere preceded the main metamorphism at c. 540 Ma. In the central DML, the earlier metamorphism occurred at 570–550 Ma and the later granulite metamorphism at 530–515 Ma. In the Sør Rondane, eastern DML, two Pan-African metamorphic events are recognized prior to the youngest granite activities: at 630–590 Ma and c. 560 Ma. The youngest post-tectonic granite intrusions occurred at $\sim$515 Ma.

The extensive granitic activities after the peak metamorphism in the DML are explained by rising of the asthenosphere to heat the adjacent crust on a large scale, as a result of continental mantle delamination after the continent–continent collision between East and West Gondwana.

Lützow-Holm Suture

The basement rocks around Lützow-Holm Bay were named the Lützow-Holm Complex (LHC). The protolith of the LHC consists of continental components of various age and origin: Some outcrops are late Archean-Paleoproterozoic crustal fragments reworked during the Pan-African event, with no indication of the Grenvillian event. Other protoliths are derived from Grenvillian juvenile crust and recycled continental sediments from the margin of the craton. Thus the prehistory of the Pan-African LHC is not uniform from outcrop to outcrop.

The peak metamorphic age of the LHC is 530–550 Ma, and indication of older metamorphic events is not clear, except for the detrital inherited ages from the metasedimentary rocks.

In the Yamato Mountains to the west, two stages of Pan-African event are suggested, at c. 640–620 and c. 550–530 Ma. These two stages are similar to those recorded in the Sør Rondane Mountains (SRM) and central DML to the further west. The younger Pan-African peak metamorphic events of the LHC compared to those of the SRM implies that it is more probable for the LHC to record the last stage of amalgamation of East and West Gondwana.

Thus the LHC may be composed of a collage of pre-Grenvillian continental crusts and Grenvillian juvenile crustal components, suggesting a marginal zone of the Napier Craton before Pan-African collision. The high-grade metamorphism at 550–530 Ma is a product of subduction. The trend of the subduction is not clear, but the progressive metamorphic grade from east to west in the LHC and the active Pan-African plutonism in the Yamato Mountains suggest the subduction toward the Grenvillian Maud crust in the west.

Thus the Lützow-Holm Complex is most likely to be a Pan-African suture and, along with the so-called Mozambique Suture, can be regarded as the eastern front of the EEAO. The inland extension of the suture can be extended either to the Prydz Bay or to Shackleton Range.

Did Rodinia Exist?

In the Prydz Bay region, outcrops of the Prydz Complex show complicated histories. Protoliths in Archean and Grenvillian basement were metamorphosed to high-grade granulite conditions during Pan-African tectonism. Some Pan-African paragneisses contain detrital zircons that suggest late Neoproterozoic (i.e., post-Grenvillian) deposition. Boger et al. (2001) proposed a continuous mobile belt that connects Pan-African tectonism in Prydz Bay with that of the southern Prince Charles Mountains. The belt continues east through outcrops along the coast of the Queen Mary Land to the Leeuwin Complex in the Pinjarra Orogenic belt of Western Australia, and west to the Lützow-Holm Complex. The age of the tectonism is inferred to be 550–490 Ma, slightly younger than the age of collision along the Mozambique Suture. Thus this Pan-African suture represents the final suture between East and West Gondwana.

Although there is debate as to whether Pan-African metamorphism in Prydz Bay can be ascribed to collision at a convergent plate margin, if it is the case, the Prydz Bay suture links with the Lützow-Holm suture at a triple junction.

Alternate interpretations of the Leeuwin-Prydz Bay suture suggest that it continues southward and inland toward the Shackleton Range or further. Some researchers have proposed that the suture extends inland, dividing East Gondwana into Australo-Antarctic and Indo-Antarctic domains.

The final amalgamation of East Gondwana may not have been complete until the Early Cambrian. Two regions of Pan-African tectonism found in East Antarctica challenged the traditional model of the Rodinia supercontinent. Although the Rodinia reconstruction of the Neoproterozoic Supercontinent has dominated discussion of the late Precambrian Earth for the past decade, other views of continent assembly have been proposed.

Furthermore, it has been argued that a succession of supercontinents existed before the stabilization of early Paleoproterozoic cratons in East Antarctica. In the absence of clear paleomagnetic data, however, it is unclear whether pre-Rodinian continental fragments with similar ages represent former supercontinents.

In conclusion, it is more likely that the East Antarctic shield was created by the juxtaposition of three separate Grenvillian-age terranes separated by two regions of Pan-African tectonism and high-grade metamorphism, in the DML and the Prydz Bay-Denman Glacier region. The DML metamorphic belt is interpreted as an extension of the East African Orogen, and the Prydz Bay-Denman Glacier metamorphic belt is regarded as extending to the Pinjarra (or Darling) Orogen in western Australia.

The East Antarctic Shield is a large continental block assembled by the Pan-African event that formed the Gondwana supercontinent. After the formation of Gondwana in the early Paleozoic, East Antarctica was cratonized and no major geological event is recorded until the extensive eruption of the Ferrar dolerite in the Jurassic.

Since East Antarctica is mostly covered by thick ice sheet, full understanding of the amalgamation and dispersal processes of the East Antarctic Shield can be completed only by investigation of the sub-ice continent with aerophysical studies or direct sampling by deep ice core drilling.

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See also **British Antarctic *(Terra Nova)* Expedition (1910–1913); Ferrar Supergroup; Geological Evolution and Structure of Antarctica; Gondwana; Lambert Glacier/Amery Ice Shelf; Plate Tectonics; Rodinia; Shackleton Range; Transantarctic Mountains, Geology of**

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ECHINODERMS

Echinoderms (particularly sea stars, brittlestars, sea cucumbers, sea urchins, and feather stars) are common and can be very abundant in the Southern Ocean. Of the world's seven thousand species, five hundred are Antarctic. The sea star *Odontaster validus* and the sea urchin *Sterechinus neumayeri* are two of the most familiar and important species in shallow waters. Echinoderms are an entirely marine group of invertebrates, with fivefold radial (the body is a hub) symmetry with a fossil record extending back to the Precambrian. The name echinoderm literally means "spiny skin" (from the Greek) but a few (sea cucumbers) do not actually have a spiny skin. They have a very unusual body based around an internal "water vascular system," which they use for feeding and locomotion. They have no brain; instead their nervous system is diffuse, so they receive stimuli equally from all directions. Most echinoderms are mobile, unlike their ancestors. Some echinoderm biologists think their great polar success is due to their bodies being mainly bone and their slow pace (a "bone idle" strategy!).

Most echinoderms are bottom dwellers, predators, detritus feeders, filter feeders, and herbivores. Some use more than one feeding strategy and others feed at more than one trophic level (on animals and algae). Many sea stars and sea urchins have been shown to be pivotal to the structure of communities; the most important are termed "keystone species" (exerting a strongly disproportionate effect on their ecosystem's structure through their predation). Echinoderms are found from the intertidal zone to the deepest ocean trenches and from tropics to poles. They are used by humans as food, as a source of medicine, as research subjects in development biology, and as ornamental accessories. Reproduction in echinoderms is typically by external fertilization; eggs and sperm are freely discharged into the water. Some species (e.g., most Antarctic echninoids) brood their eggs in special pouches. Most echinoderms go through several planktonic larval stages before becoming benthic.

The phylum Echinodermata is divided into two different groups: the subphylum Pelmatozoa exclusively includes the class Crinoidea (sea lilies and feather stars) while the subphylum Eleutherozoa includes the classes Asteroidea (sea stars), Ophiuroida (brittle stars), Concentriclycoidea (sea daisies), Echinoidea (sea urchins and sand dollars), and Holothuroidea (sea cucumbers). The Crinoidea have a rich fossil record, with five thousand known fossil species, and were most diverse between the Cambrian and Silurian periods. Most modern crinoids (six hundred species) live in deep water, but comatulids (feather stars) can be seen in the shallows. The crinoids have changed little since the Palaeozoic (250 Ma) and are considered living fossils. The twenty-two known species from the Antarctic continental shelf and surrounding oceanic islands (e.g., Bouvet, Kerguelen) are stenothermal (tolerant of a narrow temperature range) and are typically about 15 cm in size. In contrast to crinoids, sea stars and brittle stars are mainly predators or scavengers (but can be suspension feeders), and are often euryhaline and eurythermal. They are well represented in the Southern Ocean with 250 species, most of which (61%) are endemic. The sea urchins are typically algae scrapers or detritus scavengers on hard or soft bottoms. Some forty-four species are known from the Antarctic shelf, of which 57% are endemic. Sea cucumbers tend to be vagile (slow moving), soft bottom dwellers, with positive geotactism. A crown of tube feet around the mouth functions as feeding tentacles for suspension feeding or deposit feeding. The thirty-eight species recorded from coastal Antarctica have 58% endemism.

Antarctic echinoderms, particularly the sea urchins, have been important as model animal groups for scientists to study reproduction and ecological (abundance) versus evolutionary (species generation) success in Antarctica.

ERIKA MUTSCHKE

See also **Benthic Communities in the Southern Ocean; Deep Sea; Food Web, Marine; Growth; Larvae; Reproduction; Seaweeds**

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ECOSYSTEM FUNCTIONING

"Ecosystem functioning" is a very general and often imprecisely defined term that encompasses the processes and links between biota in an ecosystem through which "resources" (i.e., energy, matter) flow. The term is best understood as a means of integrating the entire food web within an ecosystem. Antarctic ecosystems are conventionally described as being very simple in structure. This can be seen at various levels, but it is most commonly expressed as their being species-poor or depauperate, dominated by "lower" faunal and floral groups, or having low trophic complexity and/or representation of higher trophic levels. While the general simplicity of these ecosystems is well known and widely accepted, at least in the context of multicellular animals and plants, and illustrations of their food webs available, there have been few rigorous attempts to prove and quantify the significance of what are often largely hypothesised links.

It is often the case that the classical view of ecosystem structure and function, derived from lower-latitude ecosystems with which we are most familiar, cannot easily be applied in an Antarctic context. Classical ecosystem structure allows the assignment of the component biota to a series of discrete trophic levels—autotrophic producers, primary, secondary, and higher-level consumers—with each of these groups also feeding into a separate decomposition pathway by which nutrients are either released for recycling into other biota or lost from biological pathways into the physical environment. In the Antarctic, ecosystems are present in which there is a progressive reduction in the presence or significance of all trophic levels. This reduction reaches its extreme limit in three very different Antarctic ecosystems: (a) those structured around endolithic microbial communities, where producers comprise algae and cyanobacteria, and consumers are represented by fungi and bacteria, which may operate either as symbionts or decomposers; (b) the hypothesised microbial ecosystems of continental subglacial lakes, which, if they exist, are likely to include little or no representation of primary producers and rely on extremely low levels of exogenous nutrient input to service the needs of a limited microbial decomposer community; (c) lake ecosystems of the maritime and continental Antarctic, which are dominated by microbial processes—the "microbial loop"—rather than a conventional metazoan food chain. Even where present in terrestrial ecosystems, true predators are yet to be demonstrated to play a detectable role in the control of populations of species at lower trophic levels. However, it is also the case that known predators, or at least facultative omnivores, are present in all terrestrial ecosystems in which multicellular fauna are present, indicating that we have much yet to understand in the functioning of these ecosystems.

A predicted, but largely untested, consequence of the overall simplicity of Antarctic ecosystems is that, as they include examples where one or more biological functional groups are not present or are poorly represented, this lack will exert a controlling influence on the form of overall ecosystem structure that can be supported. Subsidiary to this is a separate prediction that these ecosystems are vulnerable to invasion by nonnative species representing currently absent functional groups. Such invasions (e.g., the introduction of aggressive invertebrate predators to sub-Antarctic ecosystems currently lacking these) appear to be able to lead to rapid and deleterious consequences for native biota and stability of indigenous food webs, and are also predicted to become increasingly common in the event that contemporary regional climate change trends in Antarctica continue.

Peter Convey

See also **Algae; Decomposition; Fungi; Marine Trophic Level Interactions; Microbiology; Streams and Lakes; Subglacial Lakes**

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ECOTOXICOLOGY

Several thousands of synthetic new chemicals unknown to biota (xenobiotic) have come into use during the last 60 years. In the 1970s, it was recognized that anthropogenic chemicals may affect nontarget organisms and biotic communities, prompting the development of a new science: ecotoxicology. In contrast to toxicology (a much older science dealing with the harmful effects of chemicals on individual organisms), ecotoxicology is interdisciplinary and uses physicochemical, biological, and ecological parameters to characterize, understand, and predict the fate of chemicals in the environment.

Although pesticides have been neither produced nor applied in Antarctica, in the 1970s DDT-related compounds were discovered in Antarctic organisms. The understanding that harmful substances released into the atmosphere, water bodies, and soils of tropical and temperate regions may affect Antarctic ecosystems promoted the development of ecotoxicological research in this continent and the surrounding Southern Ocean. These regions are inextricably linked to global atmospheric, oceanographic, and climatic processes. They receive not only contaminants released by local human activities (scientific research and associated logistic support, fisheries, and tourism), but also trace elements, artificial radionuclides, and organic compounds from anthropogenic sources in other continents. Many organic compounds are persistent organic pollutants (POPs), which have a half-life of years to decades in soils and sediments and of several days in the atmosphere. Under ambient temperature at low latitudes, POPs may volatilize from water, soil, and vegetation into the atmosphere, where they are unaffected by breakdown reactions and are transported for long distances before redeposition. The volatilization and deposition cycle may be repeated many times and POPs assume a global-scale redistribution according to the theory of global distillation and cold condensation in polar or mountainous regions. In winter the sea ice behaves as a sink for airborne POPs, which are released into spring meltwaters. Since POPs are hydrophobic and lipophilic, with a strong partitioning in organic matter, they easily accumulate in the fatty tissues of marine organisms, especially in those at the higher levels of marine food chains. Many POPs are immunotoxic, endocrine disrupters, and tumor promoters, and Antarctic seabirds and marine mammals, which have developed few metabolic detoxification pathways for xenobiotics, are potentially exposed to their toxic effects. POP concentrations in the eggs, feathers, and internal organs of the South Polar skua (*Catharacta maccormicki,* a top predator and a scavenger bird that nests in Antarctica and migrates to the Northern Hemisphere during winter) are among the highest recorded in Antarctic organisms. Concentrations of 2378-tetrachlorodibenzo-*p*-dioxin equivalents in skua eggs are higher than those in polar-bear livers from Alaska. In contrast, trace metals occur naturally in the Antarctic environment. Several Antarctic marine organisms that evolved in isolation in an ocean with unique physicochemical characteristics, may naturally accumulate in their liver very high concentrations of cadmium and mercury, independently of human activities and global processes. Although the Antarctic and Southern Ocean environments are not pristine, they provide a baseline against which to monitor global processes.

Roberto Bargagli

See also **Bioindicators; Climate; Fisheries and Management; Food Web, Freshwater; Marine Trophic Level Interactions; Sea Ice: Microbial Communities and Primary Production; South Polar Skua; Tourism**

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EDDIES IN THE SOUTHERN OCEAN

Eddies are usually thought of as time-varying flows. In the ocean and atmosphere, the term eddy has multiple connotations. Eddies can be rings, vortices that swirl water around their centers either cyclonically (clockwise in the northern hemisphere) or anticyclonically (counter-clockwise in the southern hemisphere). Eddies can also be the transient part of a current, as distinct from the time-invariant or mean current. The role of transient ocean eddies is analogous to the role of storm systems in day-to-day weather fluctuations: they are responsible for the short time-scale variability in ocean currents. Finally, standing eddies are stationary in time and are computed as time-invariant deviations from a spatial mean, usually determined by averaging along lines of latitude.

Ocean eddies range in size from tens to hundreds of kilometers. Southern Ocean rings have been observed to have radii of between 30 and 100 km, and the predominant length-scale of other transient features is thought to be about the same size. This corresponds to the mesoscale, features that are large enough to be influenced by the Earth's rotation but small enough that many eddies can fit within one ocean basin. The baroclinic Rossby radius of deformation, L_D, is the length-scale at which gravitational and rotational effects have a comparable impact on depth-varying ocean flows. In the Southern Ocean, it varies from less than 10 km up to 30–40 km, and typical length-scales are therefore assumed to be $2\pi L_D$.

Sea-surface height measurements from satellite altimeter show that eddy variability is strong along the path of the Antarctic Circumpolar Current (ACC). Much of the variability is associated with the northward and southward meandering of the jets that make up the ACC. In addition, some of the variability is linked to warm-core or cold-core rings that have separated from the ACC jets and move independently. Baroclinic instability, the intrinsic variability of a fluid that becomes denser with increasing depth, is thought to be responsible for most of the observed eddy variability.

Eddies may also occur because of topography, either as lee waves downstream of topography or as Taylor columns located directly over topography. Since seafloor topography does not change position, at least on the timescales of eddy motion, these are usually thought of as standing eddies. However, if standing eddies experience small displacements, then they can be associated with enhanced transient variability. Altimeter data indicate high levels of transient eddy variability in regions where topographic lee waves are predicted. These regions occur eastward (or downstream following the flow of the Circumpolar Current) of Îles Kerguelen in the southern Indian Ocean, of Macquarie Ridge south of New Zealand, and of Drake Passage between South America and the Antarctic Peninsula.

Since the ACC is continuous around Antarctica, its mean flow provides no pathway to carry water southward from the low-latitude subtropical gyres. Thus eddies play a critical role in explaining the transport of heat, freshwater, and other properties across the ACC. For the most part, eddy transports are thought to carry properties along isopycnals, surfaces of constant density, rather than mixing waters of different densities. Overall, air–sea heat fluxes and upper-ocean transport estimates suggest that eddies carry roughly 0.45×10^{15} W of heat poleward across the ACC in order to maintain the heat balance of the high-latitude ocean. These estimates are consistent with eddy heat-flux estimates obtained from current meter observations and autonomous subsurface floats. In most estimates, regions with high transient eddy variability are also associated with high eddy heat flux.

In addition to transferring heat, eddies also transfer momentum, both horizontally and vertically. Observations from altimetry and current meters now indicate that horizontal eddy fluxes are small and have comparatively little effect on the mean flow. However, eddy fluxes are thought to be largely responsible for carrying momentum downward from the surface, where it is input by the wind, to the sea floor, where it can be transferred to the solid Earth. Downward transport of momentum is carried out by "interfacial form stress," the pressure work done by one layer of the ocean on the layer below. This pressure work can be expressed as a poleward eddy density flux, and it is commonly approximated as an eddy heat flux. Thus, eddies imply a clear link between the heat flux across the ACC and the dynamics required to balance wind forcing.

Eddies can influence biological productivity in several distinct ways. They can help to transport nutrients into otherwise low-nutrient surface waters, either through cross-frontal horizontal exchanges or through vertical exchanges. For example, the center of a cyclonic ring can be a region of upward vertical velocity, which can help bring nutrients from the deep ocean. Nutrients can be trapped within an eddy's surface layer, increasing their residence time within a particular region and therefore allowing a biological bloom to develop. Eddy processes can also influence productivity if they permit a shallow mixed layer to develop, thus trapping nutrients and phytoplankton at depths where sunlight is readily available.

Although Southern Ocean eddies have significant impacts on circulation, temperature patterns, and biology, their small length-scales make them difficult to observe and also difficult to resolve in global-scale numerical ocean circulation models. As a result, eddy processes are parameterized in ocean models, usually as diffusive processes. Typical parameterizations assume that eddies diffuse heat and momentum either horizontally or along density surfaces; in some cases, modelers allow the diffusion parameter to vary spatially depending on local conditions. The details of the global meridional overturning circulation can be sensitive to the exact form of the parameterization used for eddy processes; as a result, the impact that eddies might have on future climate scenarios has not yet been fully explored.

SARAH T. GILLE

See also **Circumpolar Current, Antarctic; Kerguelen Islands (Îles Kerguelen); Scotia Sea, Bransfield Strait, and Drake Passage, Oceanography of; Southern Ocean Circulation: Modeling; Thermohaline and Wind-Driven Circulations in the Southern Ocean**

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ELLSWORTH, LINCOLN

Lincoln Ellsworth (1880–1951) was the first to fly an airplane across Antarctica; he also explored by air its interior, and sponsored two other explorers. Born the son of James Ellsworth, a man of wealth who owned mines in Pennsylvania, Lincoln Ellsworth lived much of his early years in Chicago, and with grandparents in Hudson, Ohio. Although his opportunities were many, Ellsworth struggled to find a career that held his interest. Stories by President Theodore Roosevelt about the American West and about life outdoors inspired him. Wyatt Earp became his lifelong hero. Like Roosevelt, Ellsworth had an extraordinary interest in physical fitness and typically walked miles daily. Between 1903 and 1906, he learned surveying and planned railroad routes through rugged parts of Alaska and Canada. Throughout his life, Ellsworth had a continuing interest in natural history and traveled often to the Grand Canyon, Africa, and South America.

Polar exploration offered Ellsworth opportunities for sightseeing, adventure, and accomplishments. Stories about explorers such as Robert E. Peary, Frederick Cook, and Robert Falcon Scott convinced Ellsworth to undertake polar exploration himself. In October of 1924, he traveled to New York City, where Roald Amundsen, the most famous polar explorer in the world, was lecturing and raising money. Ellsworth offered to help Amundsen financially in exchange for participation on an expedition. Amundsen and Ellsworth met with James Ellsworth and persuaded him to provide $50,000 for an expedition north from Greenland in 1925.

> The primary objective of the new expedition was to fly two airplanes across Greenland to the North Pole. However, one of the two Dornier flying boats suffered engine failure and landed on the ice, although without loss of life; the other landed safely but quickly froze. The party lacked a radio to call for help and remained stranded for 25 days in May and June of 1925. Finally, they freed one of the planes and reached a ship at sea.

Undaunted, Ellsworth partnered with Amundsen again in 1926. This time, their goal was to fly an airship, more reliable than an airplane, from Spitsbergen, across the North Pole, and land in Point Barrow, Alaska. Money inherited from the estate of James Ellsworth, who had died while Lincoln was in Greenland, enabled them to buy an airship, *Norge,* which had been designed by an Italian, Umberto Nobile. On May 11, two days after Richard Byrd and pilot Floyd Bennett claimed to have flown over the North Pole from Spitsbergen, *Norge* took off. Nobile, Amundsen, Ellsworth, and an international crew reached the North Pole on May 12, and the next day landed the damaged *Norge* at Teller, Alaska.

In 1930, 2 years after the death of Amundsen, Ellsworth teamed up with Sir Hubert Wilkins. Wilkins had succeeded in flying an airplane from Point Barrow to Spitsbergen in 1928. The Wilkins-Ellsworth Trans-Arctic Submarine Expedition tried to explore the Arctic under the ice. Ellsworth provided financial support and served as science adviser, but Wilkins led the enterprise. Although *Nautilus,* a renamed submarine from World War I, suffered mechanical difficulties that limited its success, Wilkins and Ellsworth began a lifelong friendship and partnership.

Aided by Wilkins, Ellsworth determined to make his own mark in Antarctica as the first to fly an airplane across the continent. Apart from the adventure and prestige, Ellsworth expected to add to knowledge about the largely unknown interior of the continent. Geographers and explorers wanted to know if a channel connected the Weddell and the Ross seas. Others questioned whether the Queen Maud Mountains might stretch across the continent to Graham Land on the Antarctic Peninsula.

Ellsworth and Wilkins prepared meticulously for the flight. The expedition commissioned the Northrup Corporation to build a special airplane, *Polar Star*. Made of metal, it had a range of about 7000 miles (11,200 km). Its low wings enabled its two passengers to scoop a trench under the plane to install a landing gear with skis. Thus, the plane could land on an unprepared runway of snow and take off again. To design and pilot *Polar Star*, Ellsworth hired the experienced Bernt Balchen, the Norwegian flier who had flown with Byrd over the South Pole in 1929.

In January of 1934 Ellsworth's ship, *Wyatt Earp*—a redesigned Norwegian vessel—took Ellsworth and his party of seventeen to the Bay of Whales in Antarctica. It would be the first of three efforts by Ellsworth to fly across the continent. It began disastrously when ice cracked and damaged the airplane. In October 1934, a second attempt began when *Wyatt Earp* reached Deception Island. Unfortunately, a connecting rod on the airplane broke, and there was no replacement. After returning from Chile with a new rod, the weather had warmed so much that Deception Island no longer suited as an airfield. Instead, the party made its way to Snow Island and found that the ice was still frozen. Weather and menacing forecasts from Richard Byrd's base at Little America on the Ross Ice Shelf delayed takeoff until January 4, 1935. That flight lasted only 2 hours. Balchen turned back to Snow Island back because he detected changing weather. This decision, which Ellsworth had opposed, ended the expedition.

In November 1935 Ellsworth returned to Antarctica with *Polar Star* for a third attempt. He changed his base to Dundee Island and brought with him two Canadians as pilots, Herbert Hollick-Kenyon and J. H. Lymburner. On November 20, Ellsworth and Hollick-Kenyon took off but returned because of a broken fuel gauge. Finally, on November 22, they began their successful flight. Twenty-three days later, during which they landed and made three camps to avoid bad weather and make observations to check their position, Ellsworth and Hollick-Kenyon succeeded in reaching the Bay of Whales. They found Little America, the base that Byrd had left in February of 1935, under snow on the Ross Ice Shelf. There they remained to await *Wyatt Earp*. Unexpectedly, an Australian ship, *Discovery II,* reached them first. This ship had been sent at the request of Sir Hubert Wilkins, when failures in radio communication from Ellsworth caused concern.

In 1936 the US Congress awarded Ellsworth a special gold medal for his achievements. The series of flights had covered 2000 miles (3200 km), of which approximately 1200 miles (1900 km) had been seen for the first time. At each of the landings, Ellsworth had taken sun sights to confirm their navigational position and to claim land for the US. His flight proved that the Weddell Sea and the Ross Sea were not connected and that previously unknown mountains—the Eternity Range and Sentinel Range—extended across Antarctica. All in all, the expedition provided a basis for the US to claim some 350,000 square miles (900,000 km^2), including the land Ellsworth named in honor of his father.

Ellsworth's last trip to Antarctica had political as well as personal motivations. The United States did not recognize the claims of any nation to Antarctica. As it happened, Ellsworth's ambitions for exploration in Antarctica coincided with the US State Department's concerns that other nations, especially Germany, were seeking land and potential minerals in Antarctica. To compete with these claims became a secret agenda for the expedition.

In October of 1938, *Wyatt Earp* sailed with Ellsworth and two airplanes from Cape Town, South Africa. Ellsworth's goal was to fly over the Indian Ocean sector of Antarctica and map land not previously seen but that had been claimed. Equipped with two planes, including a new long-range one from Northrup, pilot J. H. Lymburner and Ellsworth took off on January 9 from 68°30′ S, 79° E, and reached 72° S, 79° E. Returning after two and a half hours, Ellsworth claimed 80,000 square miles (207,000 km^2)

for the United States, which he named the American Highland. Australia had previously claimed this area after Sir Douglas Mawson's BANZARE.

Ellsworth had planned to return to Antarctica and winter at the South Pole in 1941. However, World War II interrupted his plans, and then Ellsworth himself had a terrible accident. While hiking in Mexico in 1943, he suffered a severe fall that led to a concussion. This was the beginning of setbacks in health that resulted in his death on May 26, 1951. Specimens that Ellsworth had collected in expeditions to the Arctic and the Antarctic as well as safaris to remote places in Africa and South America were added to the treasures of the American Museum of Natural History. A foundation that bears his name continues to support polar history.

RAIMUND E. GOERLER

See also **Amundsen, Roald; Aviation, History of; British, Australian, New Zealand Antarctic Research Expedition (BANZARE) (1929–1931); Byrd, Richard E.; Ross Ice Shelf; Wilkins, Hubert**

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EMPEROR PENGUIN

Emperor penguins, *Aptenodytes forsteri,* largest of all living penguins, stand 1 m tall and weigh on average between 20 and 35 kg. Generally larger and more portly than king penguins, *A. patagonicus,* their nearest kin, emperors have shorter, more slender and decurved bills, and narrower blue or violet bill plates. The chest is lemon-yellow, the auricular patches (on either side of the head) are yellow rather than golden-orange, and the ankles are fully feathered. Emperors breed exclusively along the coast of Antarctica, on sea ice that is fast to the ice cliffs or on land. Adults seldom appear far from their breeding zone, but vagrants—probably young birds in their second to fourth years—are occasionally seen as far north as New Zealand, Tierra del Fuego, South Georgia, and once at Heard Island.

Discovery

A mysterious large egg, discovered on an Antarctic ice floe by the French Naval Expedition of 1837–1840, was the first indication that an unusually large penguin inhabited the Antarctic pack ice. Near-contemporary American and British expeditions brought home skins that, after initial confusion with king penguins, were finally identified as a new species and named in 1844. Later, nineteenth-century expeditions reported more of these splendid birds, but not until October 1902 was the first breeding colony discovered, by a party from Robert Falcon Scott's British National Antarctic Expedition of 1901–1904, who were visiting Cape Crozier, Ross Island. This discovery confirmed two strange facts about emperor penguins—that they incubate and rear their chicks on sea ice, and breed in the depths of the Antarctic winter.

Drygalski's German South Polar Expedition of 1901–1903 discovered a second colony, and the strong likelihood of a third was reported off the Larsen Ice Shelf by Nordenskiold's Swedish South Polar Expedition of 1901–1904; its existence was finally confirmed a century later. A fourth was found at Haswell Island by Douglas Mawson's Australasian Antarctic Expedition of 1911–1914. Meanwhile, in 1911, Edward Wilson, Apsley Cherry-Garrard, and Henry Bowers of Scott's British Antarctic *(Terra Nova)* Expedition of 1910–1913 made a mid-winter journey to the Cape Crozier colony, to collect eggs for embryological studies. Cherry-Garrard's account of the expedition, *The Worst Journey in the World,* is possibly the most celebrated of all Antarctic books. Shackleton's Imperial Trans-Antarctic Expedition of 1914–1917 collected large chicks afloat on the pack ice of the Weddell Sea, finding them a welcome addition to their diet. The discovery in 1948 of a small colony on the Dion Islands, off the west side of Antarctic Peninsula, made it possible for scientists to winter with the emperors and examine aspects of their winter breeding strategy.

Population Size

From the 1950s onward, an increasing number of expeditions were able to explore the Antarctic coastline during the winter months, locating in all between forty and fifty breeding localities, and French, Australian, New Zealand, German, and United States scientists have studied in more detail the numbers, ecology, behaviour, breeding biology, diving abilities, and vocalizations of emperor penguins.

The number of breeding colonies remains uncertain. All but two known colonies occur on the sea ice, in locations that may vary by several kilometers from year to year. For a similar reason, it is difficult to estimate sizes of colonies accurately. With no nesting sites, groups of incubating and brooding birds move and divide in the course of the winter, and a shift of wind may carry the whole or part of a colony out to sea. Among the largest known and most stable colonies is the one that forms each year near Cape Washington, Victoria Land, in the Ross Sea, estimated to include 20,000–25,000 breeding pairs. Many colonies involve 5,000–20,000 pairs, while the smallest colonies are numbered in the tens or hundreds of pairs. Some reported in early years may have disappeared, and a newly discovered colony is occasionally added to the list of known localities. A world total of approximately 220,000 breeding pairs is estimated, of which about half live in the Ross Sea area. Though estimates of individual colonies vary from year to year, there is no indication that numbers overall are decreasing. Some of the more accessible colonies are now open to visits by tourists from cruise ships.

Feeding, Swimming, and Diving

Emperor penguins feed mainly on crustaceans (particularly euphausiids), squid, and fish. Some they catch close to the surface, foraging for crustaceans and fish immediately under the sea ice. However, they are also deep divers, and may feed close to the bottom in water 400–500 m deep. On foraging journeys lasting several days they may travel over 1400 km, at mean speeds of around 2 km per hour; while hunting they can make bursts of 12 km or more per hour.

The Annual Cycle: Assembly and Courtship

Adult emperors spend late summer and autumn on the remnants of the pack ice, feeding and moulting. In late autumn, after a further bout of intensive feeding, they head southward to where the new season's fast ice is forming around the continent. By April and early May, they have gathered in their traditional areas, usually close to ice cliffs, often on sea ice that is locked and stabilized among islands or stranded icebergs. The newly returning birds, in peak condition, with ample subcutaneous and visceral fat, may have to walk and toboggan (i.e., slide on their stomachs over the snow, propelling themselves with flippers and feet), for the last 50–100 km to their colony sites.

Though the genders are superficially similar, males are on average slightly larger than females, and at the start of breeding they tend to be heavier: males average 35–40 kg, females 28–32 kg. Males usually arrive before females, taking up positions in the group from which they advertise their presence and status by calling. Females respond by approaching with similar calls, and the partners stand close together, fending off passersby with bills and flippers. They make no nest. In courtship, which extends over 3 to 5 weeks, the partners bow, call repeatedly to each other, take short walks with head flagging (flashing their brilliant auricular patches), and copulate frequently. They may be partners of previous seasons, though the proportion is low (about 15%), much lower than in species with identifiable nest sites (for example, Adálie or gentoo penguins), at which partners tend to meet repeatedly in successive seasons.

Laying and Incubation

Each female lays a single blue-white egg (mean dimensions 12.5 × 8.5 cm, mean mass 460 g), which she passes almost immediately to her partner. With his bill, he shuffles it onto the dorsal surface of his feet, covering it with a fold of feathered abdominal skin and immediately adopting a characteristic crouch. The females leave, usually within a few hours of laying, heading in groups for the open sea, which may by this time be well over 100 km distant. On a large colony all the eggs are laid within a period of 4 to 5 weeks.

After the cacophony of courtship, silence settles gradually over the colony. Incubating males, which can shuffle slightly with the egg on their feet, overcome earlier mutual hostility and stand close together, forming tightly packed huddles containing from dozens to a thousand birds. This stance they maintain for the full incubation period of 60–68 days (mean 64 days). On calm days with temperatures close to freezing point, the huddles may open, the birds standing free, shaking, stretching, and preening, always with the eggs on their feet, and eating copious amounts of snow. On cold, windy days, they pack tightly together, effectively reducing their surface area and conserving body heat.

Birds on the windward side shuffle deeper into the huddle, or move round to the lee. In this way, the huddles may move steadily downwind, some over distances of several km during the 2 months of incubation. Birds that lose their eggs may find and hold substitute eggs that others have lost. Those that cannot find substitutes lose the urge to incubate within a few hours and leave the colony. During courtship and incubation, the males lose up to 40% of their initial body mass, mostly in subdermal and abdominal fat. By the end of incubation, they look relatively thin and jaded; some that appear to have reached a limit of starvation abandon their eggs and disappear toward the sea.

All-male incubation is more efficient than shared incubation, removing the necessity for partners to make long journeys over the sea ice in winter. Winter breeding is the only way of ensuring that chicks are ready for the sea by summer, when their chances of survival are highest.

Chick Rearing

In early July, simultaneously with the first hatching, the females begin their return. Looking distinctly fresh and well-nourished, they find their partners by repeated calling, take over the chicks as they hatch, and begin immediately to feed them from the contents of their crop. Relieved by their partners, the males leave the colony in droves, returning to the sea for their first swim and feed. Away for about 3 weeks, they recover some of the body mass that they have lost (on average 12 kg, or 40% of their original mass) during their long fast.

Chicks on hatching weigh about 300 g, and are covered with thin grey down, with a striking black head and white facial mask. A chick that hatches before its parent returns may be fed by the male for over a week from a crop secretion. During the first 2 weeks the chicks grow slowly, doubling their body mass and developing a denser, warmer grey down. Thereafter the parents alternate, feeding at sea and returning to their partners at about weekly intervals. They feed only their own chicks, identified by their shrill piping calls.

At 4 to 5 weeks of age, the chicks are big enough to step down occasionally from their parents' feet; at 6 to 7 weeks they begin to cluster together in crèches. In bad weather, adults on the colony cluster around them, helping to keep them warm. As the season advances, food becomes more plentiful in the sea, open water approaches closer to the colonies, and gaps appear in the local sea ice, allowing the adults to forage closer to home. By late November, aged about 5 months, the earliest chicks have begun to moult, acquiring during 3 to 4 weeks a distinctive juvenile plumage similar to that of their parents, but with grey rather than yellow auricular patches. Though now ready for the sea, they are notably smaller than their parents, weighing only 12–15 kg. At about this time the parents cease to feed them, and prepare for their own postbreeding moult.

Breeding Success

At any time from October onward, the sea ice on which the colony is present may break away. Alternatively, in years when the sea ice persists, the young birds may have to follow their parents several km to the ice edge. Survival rates of eggs and early chicks are generally high, but decrease as the chicks grow. Their grey down is not waterproof: snowstorms at temperatures around freezing point may wet the half-grown chicks, chilling them beyond recovery. Persistent sea ice may lengthen the parents' feeding journeys and reduce the frequency of feeds, slowing growth or causing starvation. Early breakout may cause adults to abandon their half-grown chicks. Southern giant petrels *(Macronectes giganteus)* can be major predators of chicks on some colonies. Overall, breeding success is usually around 50%–60%.

Once in the water, leopard seals *(Hydrurga leptonyx)* are primary predators of juveniles. Recoveries of banded birds suggest that only about 20% reach the end of their first year, when they moult into full adult plumage. We know little of their subsequent life. Starvation, being trapped in or under the sea ice, and predation by seals and killer whales *(Orcinus orca)* are likely perils during adolescence. Young birds are reported to appear in the breeding colonies in their fourth year, and start breeding 1 or 2 years later. Those that survive the dangers of growing-up are estimated to live on average 20 years.

Bernard Stonehouse

See also **Adélie Penguin; Australasian Antarctic Expedition (1911–1914); Birds: Diving Physiology; British Antarctic *(Terra Nova)* Expedition (1910–1913); British National Antarctic *(Discovery)* Expedition (1901–1904); Fish: Overview; French Naval (*Astrolabe* and *Zálée*) Expedition (1837–1840); Gentoo Penguin; German South Polar *(Gauss)* Expedition (1901–1903); Heard Island and McDonald Islands; Imperial Trans-Antarctic Expedition (1914–1917); Killer Whale; King Penguin; Leopard Seal; Penguins: Overview; Ross**

Island; Ross Sea, Oceanography of; South Georgia; Southern Giant Petrel; Squid; Wilson, Edward; Zooplankton and Krill

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ENDERBY, MESSRS.

Rarely were Antarctic exploration and commercialism more closely tied together than during the first half of the nineteenth century by the firm of Messrs. Enderby, alternatively known as Enderby and Sons or Enderby Brothers. Founded by the brothers Samuel and George Enderby in London in the mid-eighteenth century, the company owned a number of ships involved in the northern and southern sealing and whaling fisheries. In 1775, Enderby vessels were among those sent to the South Atlantic and Falkland Islands in an attempt to establish a southern whaling fishery, and a little more than a decade later a voyage under Captain James Shields was the first to sail around Cape Horn for the purpose of extending that trade into the South Pacific.

Once the Messrs. Enderby were deeply involved in the far south, the masters of their ships were encouraged to discover new grounds, to chart new coastlines, and to contribute to the growth of geographical knowledge. This became an even more significant aspect of the company's operation after the death of Samuel Enderby, son of the founder, in 1830, when *his* sons, Charles, Henry, and George, took over the operation. Charles and George were founding members of the Royal Geographical Society—Charles was also a member of the Society's Council—and they strongly promoted geographical discovery and the extension of knowledge about natural history, in addition to their commercial interests.

The company's first major geographical discovery was in 1806, when Abraham Bristow discovered the Auckland Islands. The following year he claimed them for the British Crown, made a rough chart of them, and gathered a cargo of fur seal skins. Two years later, on a visit to South Georgia, two Enderby vessels rediscovered the mysterious Bouvetøya, and in 1825 George Norris, master of the Enderby ship *Sprightly,* "rediscovered" it yet again, this time calling it "Liverpool Island" and claiming it for King George IV.

The 1830s were the height of the Enderbys' geographical contributions in the far south, although these voyages of discovery often involved considerable financial loss to the company. In 1830 an expedition in the Enderby ships *Tula* and *Lively,* under the overall command of John Biscoe, sailed from London. Before returning in 1833, they circumnavigated the Antarctic continent, discovered Enderby Land, discovered and annexed Graham Land on the Antarctic Peninsula, and visited the South Sandwich Islands, Chatham Islands, Bounty Islands, South Shetland Islands, and Falkland Islands, in the last of which *Lively* was wrecked. However, upon their return to London, they brought only thirty sealskins.

The year of Biscoe's return, Enderby sent two more vessels, *Hopefull* and *Rose,* to extend his discoveries. However, *Rose* was crushed in the ice north of Clarence Island in the South Shetland Islands, and the expedition was abandoned.

Undeterred, in 1838 the Enderbys dispatched John Balleny, in command of *Eliza Scott* and *Sabrina,* to search for new lands and sealing or whaling grounds. This was a crucial voyage, because the Enderbys' finances had so suffered that they were forced to sell more than 80% of the shares of the vessels to other London merchants. Balleny visited Île Amsterdam and the Campbell Islands, meeting Biscoe at the latter. Passing south through areas in which ice had previously turned back Fabian von Bellingshausen's ships, on February 9, 1839, they discovered the Balleny Islands. After a fog lifted, Thomas Freeman, captain of *Sabrina,* made a landing, the first reported anywhere south of the Antarctic Circle. They later described an "appearance of land" in the vicinity of the Antarctic continent that later became known as the Sabrina Coast. Turning north, *Sabrina* was lost in a gale with all hands on March 29, 1839. *Eliza Scott* returned to England, and Balleny provided a great deal of helpful information for the British naval expedition under James Clark Ross, which was soon to depart for the Antarctic. However, Balleny returned with only 179 sealskins, and the voyage proved yet another financial disaster for the Enderbys.

The combination of the series of disastrous voyages and a fall in the profit from the southern sealing fishery struck a hard blow at the fortunes of Messrs. Enderby. Inspired by reports from Ross's expedition, in 1849 Charles Enderby leased the Auckland Islands from the British government to establish a land-based whaling station, which would be run under his subsidiary, the Southern Whale Fishery Company. In December 1849 three ships loaded with settlers, stores, and equipment with which to establish the station and attendant colony landed at Port Rosson Enderby Island in the Auckland Islands. Land was cleared for farming, for the harbour and dockyard, and for a village of eighteen buildings, which was named for the Earl of Hardwicke. However, agriculture proved impossible due to the cold climate, lack of sunshine, and heavily acidic soil. Moreover, very few whales were found by the eight ships stationed there, and the remoteness of the colony meant few other ships used the dockyard facilities for refitting, as had been expected. Many of the disillusioned colonists soon departed, and the settlement was dismantled and officially closed on August 5, 1852.

The financial setbacks caused by the Enderby settlement, atop the heavy losses on a number of the major voyages, put such a strain on the company's resources that it was forced into liquidation.

BEAU RIFFENBURGH

See also **Amsterdam Island (Île Amsterdam); Antarctic: Definitions and Boundaries; Antarctic Peninsula; Auckland Islands; Balleny Islands; Bellingshausen, Fabian von; Biscoe, John; Bouvetøya; British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); Ross, James Clark; Russian Naval (*Vostok* and *Mirnyy*) Expedition (1819–1821); Sealing, History of; South Sandwich Islands; South Shetland Islands; Whaling, History of**

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EXOBIOLOGY

The link between Antarctica and extraterrestrial environments has its origins in the fact that most extraterrestrial environments of potential biological interest are cold, polar-like environments. Antarctica has been used as an "analog" environment to understand physical and potential biological processes in extraterrestrial environments. A particularly important focus has been the planet Mars. The surface of Mars has a mean annual temperature of –60°C and in the northern latitudes there is ground ice. Patterned ground similar to that observed in Antarctica bears witness to a world that can be considered a "polar desert."

The soils and lakes of Antarctica, particularly the McMurdo Dry Valleys, have been used to develop life detection strategies and technologies for Mars; field tests in these regions predate the Viking Landers, sent to Mars in the mid-1970s. The low bacterial counts and the biomarkers that microorganisms leave are used as a basis to plan robotic missions to search for life in the ground ice and near-surface soils of Mars.

Antarctica provides clues to the nature of the cold early Martian environment, when surface liquid water was more abundant than it is now. The physical characteristics of perennially ice-covered lakes have been used to understand the physics of early ice-covered lakes on Mars, satellite evidence for which has been dramatically improving. The microbiota of the Antarctic lakes provides tantalizing insights into the way in which extreme lake environments can provide oases for life in regions where the macroclimate is otherwise hostile. Sediments within the ancient Martian lakes will one day be cored by robotic explorers and humans in the search for past life, taking their lessons from Antarctica.

Perhaps one of the greatest ironies of Antarctic exobiology is that the Antarctic itself is the location for many of the Martian meteorites that have so far been discovered. Concentrated at the edge of mountain ranges, these meteorites yield clues to the physical and chemical conditions on Mars and the potential habitability of the planet, insights that aid our understanding of Antarctica itself as a Mars analog environment.

Subglacial lakes in Antarctica are being used as analogs for the ice-covered ocean of the Jovian moon, Europa, a moon approximately the same size as our own. These lakes, which are formed under the ice sheet, have physical and geochemical processes that might bear similarities to the interior of the Europan ocean. Data from Antarctic subglacial lakes will be used to plan experiments for future robotic craft that will be sent to the outer solar system to characterize these extraterrestrial oceans and search for signs of life.

Finally, it should be emphasized that the study of Antarctica as an exobiological analog is not merely a matter of enthusiastic speculation concerning extraterrestrial life. If robotic and eventually human explorers do not find life on Mars or Europa, life in Antarctica might help answer the question "why not?'', the answer to which would be as profound and revealing as the discovery of life itself.

CHARLES COCKELL

See also **Dry Valleys; Dry Valleys, Biology of; Meteorites; Microbiology; Polar Desert; Soils; Subglacial Lakes**

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F

FALKLAND ISLANDS AND DEPENDENCIES AERIAL SURVEY EXPEDITION (FIDASE) (1955–1957)

The Falkland Islands and Dependencies Aerial Survey Expedition (FIDASE) (1955–1957) was undertaken during a period of mounting political tension between the United Kingdom, Argentina, and Chile over territorial claims to the Antarctic Peninsula. At that time, the only maps of this region were expedition charts, giving an incomplete and fragmented coverage. The British government called for a program of detailed mapping, an act of administration to demonstrate its long-established sovereignty rights.

The contract was awarded to Hunting Aerosurveys Ltd. on May 26, 1955. The main requirements were (1) to undertake vertical photography of Graham Land (Antarctic Peninsula) and adjacent islands between 62° S and 68° S; (2) to provide a framework of ground control to enable the preparation of accurate maps; and (3) to provide airborne magnetic profiles for geological investigations.

Peter Mott, the chief surveyor of Hunting Aerosurveys, was chosen to lead the expedition. John Saffrey was the deputy leader in control of flying operations. The rest of the expedition staff, mostly Hunting's employees, comprised the aircrew, engineers, radio staff, camera operators, laboratory technicians to process and develop film, surveyors, a geophysicist, a meteorologist, a doctor, a cook, and a steward.

Mott had only 5 months to make the necessary preparations for the expedition. He chartered the 950-ton Danish freighter *Oluf Sven* to transport the expedition to Antarctica, and to serve as a mobile platform from which helicopters could be deployed to allow the surveyors to establish ground control points. The crew of *Oluv Sven* were led by Captain Jan Ryge. The vessel was modified with an ice-patrol bridge and a propeller guard. Further modifications enabled it to carry 60,000 gallons of drummed aviation fuel, two Sikorsky S51 helicopters, and a prefabricated expedition hut, supplies, and the 22 expedition personnel.

Two amphibious Canso flying boats were acquired for the expedition. Their range of nearly 2,000 miles and their rugged and proven reliability meant that they were ideal for operating under harsh Antarctic conditions.

On October 22, 1955, *Oluv Sven* departed from the Port of London. The journey south included calls at Las Palmas to effect repairs to the ship's generator, Montevideo to receive the aviation fuel, and Port Stanley to take on bunkers and water. Seven weeks later, on December 3, the expedition sailed through Neptune's Bellows to arrive at Whalers Bay, Deception Island.

Deception Island, a horseshoe-shaped volcanic caldera in the South Shetland Islands, was chosen because of its sheltered natural harbor, which would allow the Cansos some protection from ice when taking off and landing. Whalers Bay was the site of the abandoned Norwegian Hektor whaling station, in which a seven-man team from the Falkland Islands Dependencies Survey (FIDS) was also based.

Most of the first austral summer was spent setting up the base at Deception Island. The 60- by 20-ft (18.3 x 6.1 m) prefabricated expedition hut, named "Hunting Lodge," was erected on concrete foundations left by the whalers. It comprised a generator room, a kitchen and mess room (complete with Esse Stove), a photographic dark room, and a fourth room for drying, checking, and storing the aerial film and print. A melt stream running past the site served as the water supply necessary for processing the film.

Two of the whale oil tanks were cut open—one to serve as a warehouse for the expedition stores, the other as a garage for a David Brown tractor. The aircraft engineers occupied a wooden hut to the east of Hunting Lodge. "Radio Control Deception" was housed in a hut on the beach. A pierced steel plank slipway was laid for the Cansos, and supplemented with corrugated iron and bricks from the whaling station. Finally, a blind radar approach landing system was mounted on Cathedral Crags.

On January 10, 1956, Cansos CF-IGJ and CF-IJJ landed in Port Foster (the interior of Deception Island), after a 6-week journey from Canada via South America and the Falkland Islands. Poor weather conditions meant that it was not until February 6 that both Cansos were airborne for their first sortie. The weather barely improved, and little flying was undertaken during the first season. Furthermore, the ailerons (the movable flaps on the wings, used to control banking and rolling) of one of the aircraft were damaged during a storm. Brackets and aileron controls were improvised from steel salvaged from the whaling station.

Before returning to the UK, Mott sailed south aboard *Oluf Sven* to establish an advance base for the aircraft. Nothing suitable was found. At the end of the first season, little progress had been made towards meeting the requirements of the contract.

During the intervening period in the UK, Mott oversaw a number of logistical improvements. A lift was mounted on *Oluv Sven* for the helicopter, and heating added in the cockpits of the Cansos. One Bell 47D helicopter, fitted with a perspex bubble and flotation landing gear, replaced the Sikorskys. *Oluv Sven* departed from Harwich on October 20, arriving back at Deception Island on November 26. The Cansos arrived a fortnight later, having achieved a supplementary complete vertical aerial photography of the Falkland Islands, used to compile the first detailed map of the islands.

Disaster struck the expedition on December 10. While positioning a ground survey party in whiteout conditions, the Bell was caught in a downdraft and crashed on Tower Island. The pilots were unharmed, but the aircraft was a write-off. Valuable time was lost whilst *Oluv Sven* returned to Montevideo to collect a replacement. A visit from HRH Prince Philip aboard the Royal Yacht *Britannia* on January 3, 1957, accompanied by HMS *Protector,* helped to boost morale, and the remainder of the season carried on without further mishap.

In total, the crew of the Cansos took 10,753 vertical photographs, covering an area of 25,000 square miles (65,000 km^2). Oblique photographs taken from the sides of the aircraft extended this by a further 10,000 miles. In total, the Cansos logged 906 flying hours. The laboratory processed 113 aerial films and produced 17,000 nine-inch (22.9-cm) square contact prints. The ground control observations were sufficient to map 6000 square miles (15,500 km^2) of the South Shetland Islands and the Antarctic Peninsula.

Today, FIDASE remains the most comprehensive systematic vertical aerial photography coverage ever undertaken of the Antarctic Peninsula. Maps of the region compiled during the 1960s and 1970s were based upon the achievements of the expedition. Furthermore, the work of FIDASE serves as a time capsule of the Antarctic Peninsula glaciers and coastline as they were in 1955–1957. It predates satellite imagery, and is now used to determine glacial retreat and coastal change.

The dilapidated remains of Hunting Lodge are visited by more than 9000 tourists a year. In 2003, it was adopted as part of an historic site under the Antarctic Treaty. As long as the building stands, it is to be protected from human disturbance.

ROD DOWNIE

See also **Antarctic Peninsula; Antarctic Peninsula, Glaciology of; Argentina: Antarctic Program; Aviation, History of; British Antarctic Survey; Chile: Antarctic Institute; Deception Island; Protected Areas within the Antarctic Treaty Area; RADARSAT Antarctic Mapping Project; Tourism; United Kingdom: Antarctic Program**

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FERRAR SUPERGROUP

The early explorers with the Scott and Shackleton expeditions to Antarctica noted the conspicuous thick dolerite sills in south Victoria Land and along the Beardmore Glacier in the Transantarctic Mountains. The formal name Ferrar Dolerite was introduced by Hilary J. Harrington in recognition of the geologist on Scott's first expedition, Hartley T. Ferrar, who first described them.

The name Ferrar Supergroup now encompasses related basaltic rocks, which include a layered mafic intrusion, pyroclastic rocks, and overlying flood basalts. Dating of the lavas and a few sills by radiometric techniques has shown that magma emplacement occurred in early Late Jurassic time (c. 180 Ma) and was of limited duration (<1 million years). Jurassic basaltic rocks in Dronning Maud Land are age-equivalent but geochemically distinct, forming a province with affinities to the Karoo of southern Africa.

The Dufek layered mafic intrusion crops out in two ranges separated by 40 km. The areal extent is estimated to be about 50,000 km^2, but depends on interpretation of magnetic data. The Forrestal Range exposes the upper evolved (silica-rich) part with a thick granophyre, whereas the Dufek Massif exposes some of the lower stratified gabbroic part, although not the base. If chromite- and platinum-bearing layers are present, they most likely occur in the hidden basal zone. The estimated thickness is 8–9 km.

Sills and dikes of Ferrar Dolerite are spread out in a linear belt over 3500 km from the Theron Mountains near the Weddell Sea to the Horn Bluff region of Wilkes Land. Sills range in thickness up to more than 700 m, but commonly are 100–200 m. Sills occur mainly in the subhorizontal Devonian to Triassic Beacon Supergroup, but a few occur in cut basement rocks and the capping basaltic pyroclastic rocks. Sills commonly migrate stratigraphically, thicken and thin slightly too abruptly, and may terminate in narrow dikes. A number of sills form inclined sheets. The Basement Sill in the Dry Valleys is exceptional in its thickness (700 m locally) and the presence of thick tongues of coarse-grained orthopyroxene–clinopyroxene–plagioclase crystals. Details of these tongues provide important information on the manner in which crystals may accumulate and layering is formed. Dikes are relatively uncommon. No dike swarms are known, and no dike has yet been found cutting the lavas.

Extrusive rocks are widely scattered, forming summits in Victoria Land and the Beardmore Glacier region. Everywhere the lavas occur they are underlain by basaltic pyroclastic rocks. These pyroclastic deposits are predominantly formed by magma/water interaction (phreatomagmatism) and consist of tuff breccias, lapilli tuffs, and tuffs. In some places these rocks are extravent stratified deposits, locally they constitute remnants of tuff cones, and in two regions they are intravent deposits filling large volcanic necks and collapse structures. The filling for these structures is mainly unstratified tuff breccia as much as 360 m thick.

Flood basalt lavas form sequences as much as 750 m thick. Individual flows range from 1 to 225 m thick. In general the flows are either relatively thin (less than about 20 m) or thick (more than about 50 m), with the thick flows occurring predominantly near the base of the sequence. The flows show a range of cooling features, including columnar jointing and quench textures caused by flooding with water. Many thick flows were probably ponded (confined by topography) and may have been fissure eruptions, although no feeder dikes have been observed. The thin flows form sets of flow lobes and may have been formed by breakout from thick flows or, possibly, were erupted from local shield volcanoes.

The highly distinctive geochemistry of the Ferrar tholeiites is also recorded in the Tasmanian tholeiites and other basaltic rocks of the same age in southeastern Australasia. Ferrar geochemistry is characterized by enriched initial strontium and neodymium isotope ratios, and by trace element patterns and ratios that indicate a strong crustal imprint. There are two quite distinct chemical types: (1) the Scarab Peak Chemical Type (SPCT), which shows strong iron enrichment, forms the capping lava flow(s), and also sills in the Theron Mountains and Whichaway Nunataks, but constitutes only about 1% of the Ferrar rocks; and (2) the Mount Fazio Chemical Type (MFCT). The bulk of the Ferrar belongs to the MFCT. The least evolved (highest in MgO and lowest in SiO_2) rocks are olivine dolerites with chilled margins having MgO of 8.5%–9.0%. Dolerite with accumulations of orthopyroxene has MgO up to 20%. Chilled margins of dolerite sills range from 9.0% down to 3.7% MgO, whereas the range for lavas is 7.5%–2.5% MgO. The more evolved MgO-poor rocks in this range are andesites rather than basalts. The full range of compositions shown by the MFCT can be explained by normal crystallization processes, which separate out minerals formed at higher temperatures, accompanied by the incorporation of no more than about 5% crustal (granitic) rocks.

The SPCT forms scattered outcrops over a linear distance of about 3000 km. These rocks have an evolved composition and the same crustal imprint as the MFCT. It is remarkable because the initial isotope ratios of strontium and neodymium and the major and trace element abundances from all analyzed rocks throughout the Transantarctic Mountains fall largely within analytical uncertainty. This remarkably uniform geochemistry is the basis for suggesting a single point of origin for Ferrar magmas in the Weddell Sea region and long-distance crustal transport. The distribution of the extrusive rocks and concentrations of large volumes of dolerite suggest the magmas may have risen at a limited number of sites, including the upper Beardmore Glacier region and the Dry Valleys region of south Victoria Land. These sites were the centers of the initial explosive eruptions and subsequent effusion of flood basalts. In north Victoria Land, sills must postdate extrusive activity and the same may apply elsewhere.

The Ferrar Supergroup is the expression in Antarctica of the initial breakup of Gondwana. Magma distribution from the Weddell Sea region appears to have been controlled by preexisting Lower Jurassic rift structures that were parallel with the not-far-distant Late Paleozoic–Early Mesozoic subduction margin of the Gondwana plate.

David H. Elliot

See also **Dry Valleys; Geological Evolution and Structure of Antarctica; Gondwana; Transantarctic Mountains, Geology of; Victoria Land, Geology of; Weddell Sea Region, Plate Tectonic Evolution of**

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FICTION AND POETRY

Poetry aside, in its broadest sense Antarctic fiction encompasses novels, treatises, short stories, children's stories, and even drama. From the earliest authors (writing before the age of Antarctic exploration) to latter-day writers, much fiction continues to define the Antarctic as a mysterious, imaginary space populated by otherworldly people, strange creatures, and extraordinary occurrences located in fantastic geography. While many stories emphasise the otherworldliness of the Antarctic (sometimes as a comparison to their own cultures), only in the late twentieth century did novels begin to appear where the Antarctic was the stage for more catastrophic global fears including volcanic eruptions, wars, and melting ice.

Generally believed to be the earliest example of preexploration Antarctic fiction, Bishop Joseph Hall's Mundus *Alter Et Idem* (1607) imagined the Antarctic as a satirical foil to criticise contemporary culture. Anthanasius Kircher, another early writer, fancied the Earth to be open at the poles, in his *Mundus Subterraneus* (1665), a motif perpetuated in the age of exploration by Captain Adam Seaborn's *Symzonia* (1820) and Edgar Allan Poe's novella *The Narrative of Arthur Gordon Pym of Nantucket* (1838) (written as the American Exploring Expedition [1838–1841] was about to depart). While the mid-nineteenth century produced occasional works of realism such as *The Sea Lions* (1849), James Fenimore Cooper's novel about seal hunting, the remainder of the century continued to be dominated by fantasy novels such as James de Mille's *A Strange Manuscript Found in a Copper Cylinder* (1888), Rudyard Kipling's *The Jungle Books* (1893), and Jules Verne's *Le Sphynx des Glâces* (1897).

By the twentieth century Antarctic expeditions were obliquely, but identifiably, the subject matter of fiction. Allan Villiers' *Whalers of the Midnight Sun* (1934) dealt with Antarctic geographical discoveries while detective novels like Hammond Innes' *The Survivors* (1949) drew heavily on Shackleton's *Endurance* expedition (1914–1916), and the plot of Thomas Keneally's *Victim of the Aurora* (1977) was populated by characters similar to Scott's final *Terra Nova* Expedition team (1910–1913). More recently, a spate of disaster novels centred on environmental change, like Thomas Block's *Airship Nine* (1984) and Richard Moran's *Cold Sea Rising* (1986), have shared the Antarctic stage with a new generation of novels more obviously centred on Antarctic expeditions. These include Caroline Alexander's *Mrs. Chippy's Last Expedition* (1997), a journal of the cat that accompanied Shackleton's *Endurance* expedition, and Adrian Caesar's *The White* (2001), a fictional rendering of the final days of Scott's *Terra Nova* Expedition.

Many of the early Antarctic short stories fell into the mystery and horror genres, which were ideally suited to the impact of reading stories at a single sitting—a key characteristic of the short-story form.

In the nineteenth century, Edgar Allan Poe's "MS Found in a Bottle" (1833) (written to coincide with the return of the American Palmer-Pendleton Expedition, 1829–1831) and "The Unparalleled Adventures of One Hans Pfaall" (1835) capitalised upon the Antarctic regions as a terra incognita ripe for marvellous occurrences and the fictionalisation of popular theories. In "MS Found in a Bottle," Poe's protagonist disappears into a hole at the South Pole seemingly in fulfilment of John Cleves Symmes' theory of a hollow earth composed of concentric spheres, connected (and with possible transit) between the poles.

Short stories written by explorers themselves include Douglas Mawson's "Bathybia" and A. F. Mackay's "An Interview with the Emperor" in *Aurora Australis* (1908), which took as their subject matter the British Antarctic *(Nimrod)* Expedition (1907–1909). Exploiting the mysterious nature of the South Polar regions, short stories from the 1930s and beyond became a staple not only of the mystery and horror genres, but also science fiction, appearing in such pulp magazines as *Astounding, The Macabre Reader, Alfred Hitchcock Mystery Magazine,* and *Analog Science Fiction and Fact*. These and later examples include S. W. Ellis' "Creatures of the Light" (1930), J. M. Leahy's "In Amundsen's Tent" (c. 1930), Ursula LeGuin's "Sur" (1982), Emmy Lou Schenk's "Ice Cave" (1987), and Brenda Clough's "May Be Some Time" (2001).

Although often ignored, children's stories dominated by penguins, exploring heroes, adventuresome children/adults, and even rocket ships have proved an extraordinarily durable staple of Antarctic literary output. Early examples of adventure literature include William Kingston's *At the South Pole; or, the Adventures of Richard Pengelly, Mariner* (1877) and G. Stables' *In the Great White Land: A Tale of the Antarctic Ocean* (1903). From the 1930s to the 1950s science fiction stories involving individuals armed with suitably impressive technology proved very popular with boys. Examples include C. Farrell and H. Colson's *Jack Swift and His Rocket Ship* (1934) and V. Appleton's *Tom Swift and His Atomic Earth Blaster* (1954). In more recent years younger children have been deluged with a plethora of "penguin stories" including Joyce Holland's *Bessie, the Messy Penguin* (1967), A. Wood's *Little Penguin's Tale* (1989), and Tim Weare's *I'm a Little Penguin* (2002).

Written the year before Robert Rhodes mapped the east coast of Kerguelen, Samuel Taylor Coleridge's poem "The Rime of the Ancient Mariner" (1798) is one of the earliest and perhaps most famous examples of Antarctic poetry. It was followed by a dearth of poetical output in the nineteenth century that was balanced only by the more prolific twentieth century. A steady trickle of Antarctic poetry followed the beginnings of 1901 expeditions by the Swedish (under Nordenskjöld), Germans (under Drygalski), and English (under Scott). Poetry focussed on aspects of Antarctic exploration, its difficulties (including scurvy), its history, and more generally on the qualities of the Antarctic itself. Examples (much of them published by the *Bulletin*) are W. T. Goodge's "The Value of Knowledge" (1909), Rose de Boheme's [Agnes Rose-Soley's] "The Joys of Antarctica" (1912), Iford's [Charles Hayward's] "Vitamin C" (1937), J. E. G. Channon's "Mawson to Queensland: South" (1960), and Mary Dilworth's "Air Disaster Antarctica" (1993).

Like Antarctic fiction, the region's poetry was sometimes written to coincide with popular interest in Antarctic expeditions and was occasionally penned by the explorers themselves musing on their own endeavours. Examples are Veritas' [Ernest Shackleton] "Midwinter Night," Nemo's [Ernest Shackleton] "Erebus," and Lapis Linguae's [Eric Marshall] "Southward Bound," all in *Aurora Australis* (1908), which took as their subject matter the British Antarctic *(Nimrod)* Expedition (1907–1909). Another example of an explorer writing poetry is Douglas Mawson's "The Silence Calling" (published posthumously 1977).

R. J. Cassidy published "The Southern Sacrifice" in 1912, the same year as Scott's ill-fated attempt to reach the South Pole, while Dorothy Porter published "Wilson's Diary" (1982) and "Oates' Diary" (1989). There has been a rediscovery of the Antarctic and Antarctic themes and a move towards epic poetry of considerable length. Examples include C. B. Orsman's *South: An Antarctic Journey* (1996) and Melinda Mueller's *What the Ice Gets: Shackleton's Antarctic Expedition 1914–1916 (A Poem)* (2000).

Drama focused on the Antarctic, although scant, is currently on the increase. The nineteenth century witnessed only one known Antarctic play, titled *South Polar Expedition,* which was performed in Hobart, Tasmania on 3 May 1841 and was possibly timed to coincide with the homeward-bound American Exploring Expedition (1838–1841). In the early twentieth century B. Espinasse published *Australis; or, The City of Zero* (1900) and Antarctic explorers, rather than the Antarctic, provided the raw materials for a rendition of *Ticket of Leave*. Adapted from Watts Phillips' play and performed by Gilbert Scott, Frank Wild, and Horace Buckridge, members of Scott's Discovery Expedition (1901–1904), both Scott and Buckridge played female roles. In 1941 Australian radio broadcast Stewart Douglas' *The Fire on the Snow* and only one play per decade was published in the 1970s–1990s. However, in the late twentieth and early twenty-first centuries New Hampshire witnessed *Endurance* by Louise Smith in 2000 while the London stage hosted David Young's *Antarctica* in 2001 (first performed in Canada, 1998).

IAN N. HIGGINSON

See also **Books, Antarctic; British Antarctic *(Nimrod)* Expedition (1907–1909); British Antarctic *(Terra Nova)* Expedition (1910–1913); British National Antarctic *(Discovery)* Expedition (1901–1904); Imperial Trans-Antarctic Expedition (1914–1917); Mawson, Douglas; Scott, Robert Falcon; Shackleton, Ernest**

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FIELD CAMPS

Antarctic field camps are temporary, summer-only camps that are set up at sites remote from permanent bases or stations. Field camps have been an important part of life in Antarctica since humans first landed on the continent. Early exploration of Antarctica relied on small field parties hauling sledges loaded with all the equipment they needed for survival. The camps they set up did not look very different from a small field camp today with pyramid ("Scott") polar tents, sleeping bags, cookers, and food supplies.

Today field camps are most commonly used as a means of studying a remote site intensively, thereby eliminating the need to transport people back and forth between the camp and the permanent base, or as a jumping-off point for various scientific studies in the vicinity of the field camp. Field camps are also used by modern explorers as they travel across the continent or set up base camps to explore specific parts of the continent.

Modern field camps vary from small tent-based camps reminiscent of the early explorers to camps that might house more than fifty people and provide infrastructure for high-tech scientific studies. How these camps are supported and what they consist of depends on the distance that the camp is from the permanent base, the number of people to be supported at the camp, and the duration that the camp is to be located at the site.

The United States Antarctic Program, for example, staged a major deep-field camp in the late 1970s on the Darwin Glacier, 150 miles south of McMurdo Station. This camp was for geologic and glaciological investigations. It housed up to fifty-eight people at any one time, and three helicopters were based at the camp to transport researchers around the area. This helicopter capacity enabled the establishment of satellite camps up to 110 miles from the main camp.

In contrast to this, while attempting to cross Antarctica unassisted from November 2000 to February 2001, modern adventurers Liv Arnesen and Ann Bancroft camped in one tent for their 94-day expedition. They set up their field camp at the end of a day of hauling their sledges by ski. The sledges contained everything they needed to survive.

Field Camp Set-Up

Field camp set-up or "put-in" can be supported in a number of ways, depending on the distance the camp is from the permanent base and the terrain to be covered to reach the site. For relatively short distances over easy terrain for overland vehicles, tracked vehicles such as Hägglunds, Caterpillar tractors, and snowmobiles can be used to transport the camp cargo overland or over sea ice on sleds. This brings with it the challenges of crevasse and sea-ice-crack crossings.

Camp put-ins by air are more common for sites several hundred miles from the permanent base. Ski-equipped, fixed-wing planes are used for this purpose. Twin Otters (with payload of approximately 1000 kg) are used by the British, United States, New Zealand, and Italian Antarctic programs, for example, and Hercules LC-130s (with payload of approximately 5000 kg) are used by the United States Antarctic Program. Temporary ski-ways are often set up at the field camp to accommodate these flights.

For flights within a couple of hundred kilometres, and to sites where ski-equipped aircraft are unable to land, helicopters are the preferred mode of transport. Fuel caches situated between the permanent base and camp location are often needed to support such flights.

Ship transport can also be a means of putting a field camp in at coastal locations, and is often used by the Australian Antarctic Division, for example.

Tents/Structures

Field camp sizes can vary from small, self-sufficient camps of two people housed in tents, to larger camps accommodating fifty people or more in a variety of large semipermanent structures.

The most commonly used tent for accommodation is the Polar or Scott tent, which is a modified version of the tents used by Captain Scott in the early 1900s. This is a four-poled, double-walled, pyramidal tent with a cloth tubed entrance and canvas floor. These tents are designed to sleep, cook, and eat in with ventilation holes in the roof, and are recognised as the most resilient to the Antarctic conditions.

Modern four-season mountain tents are also used for accommodation purposes, particularly in areas that are less prone to severe Antarctic conditions, and where weight and space are an issue for transportation.

Larger semipermanent structures can serve as accommodation, kitchen and dining facilities, research, recreation, or mechanical maintenance areas. Heaters are installed in these to keep the ambient temperature above zero. Examples of such structures are Weatherhavens™, Jamesways, or Rac-Tents. These have wooden floors with framing that supports a canvas or wool covering over it and are large enough to walk around freely inside. Jamesways and Rac-Tents are constructed by adding a number of sections together, which allows for flexibility in the size of the structure that is built.

Small, curved, lightweight, fibreglass huts are called "apples." These can be flown intact into a campsite by helicopter, set up on uneven ground, used for both accommodation and cooking, and easily extended with the addition of a second "apple."

The Australian Antarctic Division has recently introduced "tank-huts" into its sub-Antarctic operations. These are polymer water tanks that have been converted into accommodation modules with the addition of internal insulation, a doorway, and windows. These can be sealed up and floated ashore to coastal field campsites with the aid of additional flotation devices.

Converted refrigerating shipping containers are often used for camps located close to a permanent base. They are insulated, and can be hauled on sledges in a convoy train across sea ice or snow and are ideal for longer-term camps. The multinational Cape Roberts Project (Australia, Germany, Italy, New Zealand, The Netherlands, United Kingdom, and United States) operated over three seasons in McMurdo Sound using a variety of converted containers for accommodation, cooking, dining, and research laboratories.

Science Facilities

Field camps supporting scientific activities often need to cater to a range of different science technologies. These may be as basic as providing the facilities for samples to be analysed by microscope in the field, or enabling the use of computers, to more sophisticated facilities for logging, analysing, and storing sediment or ice cores. As such technologies have developed, there is a growing pressure on national Antarctic programs to provide facilities to support such work in the field.

Sleeping

Field-camp personnel usually sleep on a camp stretcher and/or on insulated matting. Containers and some of the other semipermanent structures may have bunk beds built in them. One or two sleeping bags made of natural or synthetic fibres are used. This system has changed little over time.

Food and Food Preparation

Traditionally, dehydrated foods and those high in fat content such as butter and chocolate have been used in field camps. Dehydrated foods reduce the amount of cargo weight for the put-in and any subsequent transport of the camp. Prepacked ration food boxes have a specific number of person food days in them, so the required number of food boxes are taken to cover the field period, including additional amounts for emergencies. More recently, some Antarctic programs such as the New Zealand and United States programs have moved towards frozen foods to replace the often bland and repetitive dehydrated foods. Meat, fish, cheese, vegetables, and breads can all be taken into the field and kept frozen for use when required. "Freezers" can be dug in the snow to protect the foods from the sun and potential thawing. Although this shift does bring some variability into the diet, cargo weights are increased and there is a higher risk of the food's spoiling before it is eaten.

Food preparation depends on the size of the camp and the amenities that are available. In smaller camps made up of a few Polar tents, cooking is undertaken in the tents using small primus stoves. In the larger camps, Coleman stoves, gas burners, and even microwaves, electric stoves, and ovens are used.

Water-making is key at any field camp. Depending on the site, water can be sourced by melting glacier ice (which yields a higher water content per unit of volume compared to snow), snow, surface sea ice, or naturally occurring melt streams off glaciers or snow patches.

Waste

There has been a big shift in the methods of waste disposal from field camps. Until the 1990s field waste was often burnt or buried on site. Many programs now ban the burning of waste in the field and waste is returned to the permanent base for disposal. On the polar plateau, human waste is still buried in the snow and ice, but on ice-free land, the return of human waste to the permanent station is encouraged and often enforced by legislation.

Communication

The most common form of communication from the field is High Frequency (HF) radio. In the 1950s and 1960s Morse code was used to communicate over the low-powered HF systems, as Morse could penetrate the static better than voice. As technology developed in the 1970s there was a shift away from Morse towards voice communication. A difficulty that continues to plague HF communications is solar flare activity, which disrupts the radio waves. This is particularly troublesome as field camps are usually required to make contact with the main base on a daily basis. Failure to make contact results in the initiation of search-and-rescue procedures. In many instances the use of satellite telecommunications has overcome this difficulty as these are not disrupted by solar activity. However, a good sight of the northern skyline is necessary, as communication is reliant on satellite coverage, which is often hard to obtain in the higher latitudes. Portable satellite phones and relatively small base stations mean that HF can be backed up by satellite communications if needed.

Very High Frequency (VHF) radio contact is mostly used for line-of-sight communications. VHF repeaters broaden VHF networks to cover large areas not in the line of sight and can make VHF more effective than HF communications. Such a repeater network is used in the Dry Valleys area of Victoria Land, where the network connects the New Zealand, United States, and Italian operations.

Energy Production

Power generation for small camps with limited power needs can be provided by small solar panels to recharge radio batteries, and small generators to power laptops. As camps and scientific projects grow in size and complexity, energy demands increase. These have traditionally been met by petrol or diesel generators. More recently, programs are moving towards alternative energy where possible, realising the logistical and environmental efficiencies of using less fuel. Solar power and wind energy have been used to power basic camp needs, though generator power is usually needed for backup.

Staffing

The number of field camp support staff depends on the size and purposes of the camp. If travel in potentially dangerous areas away from the camp is needed, then field safety staff members are used to ensure safe travel in these areas. Larger camps often have a camp manager, to coordinate flights, movements in and around camp, and the general smooth and safe running of the camp; a cook; and, depending on the facilities at the camp, a mechanic. Often, one person can cover the role of several of these needs.

Transport In and Around a Field Camp

The mode of transport used in the field depends largely on the purpose and permanence of a field camp. In the 1950s and 1960s some programs (for example Australian, British, and New Zealand) relied on dog teams to move their camps from site to site or to travel to areas away from a camp. A team of nine dogs could haul a sled of up to 680 kg. Travelling at an average speed of four miles per hour, the dogs proved to be useful crevasse probes in treacherous glaciated terrain.

Snowmobiles came into use in the mid-1960s and slowly replaced the dog teams, although they initially travelled only marginally faster and had difficulties going uphill. Early snowmobiles often needed to be accompanied by a mechanic as they were so unreliable. Since the late 1960s, advances in technology have now made snowmobiles a much more reliable and faster form of transport in the field.

Other vehicles used in the field include all-terrain vehicles (Quad bikes) and tracked vehicles such as Hägglunds, which are used by the New Zealand, Norwegian, Swedish, and United States programs.

Navigation

Methods for early navigation around field camps depended on where in Antarctica the camp was situated. At sites on the Antarctic Peninsula a magnetic compass could be used with relative accuracy. However, at other sites, such as those in the Transantarctic Mountains, this method was hampered by the fact that the geographic South Pole was in one direction and the South Magnetic Pole in another. In this case, theodolites, sun compasses, or sextants were employed, which used the angle of the sun and time of day to determine location.

The more recent advent of satellite Global Positioning Systems (GPS) in the 1980s revolutionised polar navigation. Although they were costly and cumbersome when first developed, accurate, handheld GPS units are now the norm.

Safety

Safety at field camps is paramount, as they are often located at remote sites where immediate assistance is not possible. Camp personnel receive first-aid training. National Antarctic programs have safety protocols in place for various operations such as linked snowmobile travel, walking/skiing over crevassed terrain, making scheduled radio contact with the permanent base, and procedures for calling for emergency assistance. Survival bags are deployed for travel away from the camp. These contain emergency food and shelter.

SHULAMIT GORDON

See also **Adventurers, Modern; Antarctic Peninsula; Australia: Antarctic Program; Aviation, History of; Dogs and Sledging; Dry Valleys; Italy: Antarctic Program; McMurdo Station; New Zealand: Antarctic Program; Norway: Antarctic Program; Scott, Robert Falcon; South Pole; United Kingdom: Antarctic Program; United States: Antarctic Program**

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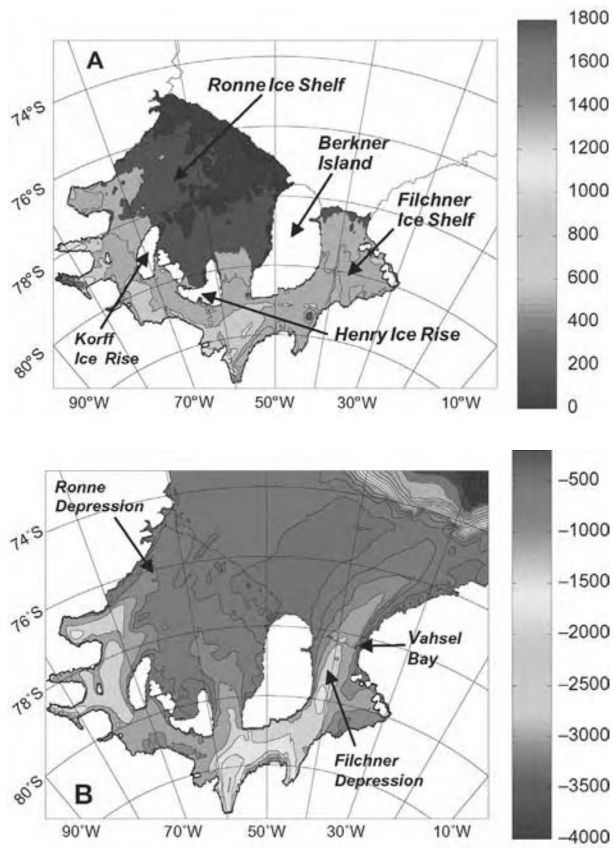
FILCHNER-RONNE ICE SHELF

Filchner-Ronne Ice Shelf (FRIS), situated in the southern Weddell Sea, is the largest body of floating ice on the planet, containing nearly 350,000 km^3 of ice. Although it is slightly smaller in area than its Ross Sea counterpart, Ross Ice Shelf, its average thickness is more then 50% greater. The separate names of Filchner Ice Shelf and Ronne Ice Shelf are generally applied to the regions lying to the east and west, respectively, of Berkner Island. However, there is no clear glaciological distinction between the two.

FRIS is fed by the flow of ice from grounded portions of the ice sheet, snowfall on its upper surface, and freezing of seawater to its base. The majority of the inflow is carried from the Antarctic ice sheet via nine fast-flowing ice streams. A much smaller proportion comes from the Antarctic Peninsula and regions of grounded ice, known as ice rises, enclosed within the ice shelf. Together these sources make up about two-thirds of the input. The vast majority of the remainder comes from accumulation. Basal freezing makes only a small contribution to the net balance of the ice shelf, because most of the frozen-on ice is melted off again before it reaches the ice front. Net melting (the amount by which basal melting exceeds basal freezing overall) removes about half of the ice that flows in from the grounded ice sheet (i.e., about one-third of the total input). Calving of icebergs from the ice front accounts for the remaining two-thirds of the mass loss. The icebergs comprise a roughly 50/50 split between ice derived from the grounded ice sheet and that derived from surface accumulation on the ice shelf.

Near the inland margin the ice is around 2 km thick in some places. The thickness gradually declines towards the ice front, where it ranges from 150 to 500 m. The structure of the ice shelf varies laterally. The fast-flowing ice streams produce thick tongues of ice, while thin ice forms between them in the wake of promontories of grounded ice and ice rises. Melting and freezing driven by an "ice pump" mechanism removes ice from the bottom of the thick tongues and deposits it in the intervening channels of thin



Maps of Filchner-Ronne Ice Shelf and the continental shelf to the north showing (A) ice thickness and (B) seabed elevation, both in metres.

ice. In this way variations in the total ice thickness are smoothed out and layers of marine ice up to 350 m thick are formed. Marine ice accumulates by intense freezing over a limited area, and is subsequently carried downstream to form long tongues that gradually thin as a result of longitudinal stretching and basal melting.

The oceanic water column beneath the ice shelf averages around 350 m in thickness, and in places it exceeds 1 km. The areas of maximum thickness are far within the cavity over deep seabed trenches, the Ronne and Filchner Depressions, which are prominent features of the continental shelf that extend to the north of the ice front. Away from the grounding line, the area of minimum clearance between the ice base and seabed, in places only about 100 m, lies at the ice front to the east of Berkner Island.

The continental shelf beyond the ice front represents one of the most southerly parts of the open ocean. (The furthest point south attainable by a surface ship alternates between Vahsel Bay in the Weddell Sea and the Bay of Whales in the Ross Sea, dependent on the cycle of advance and calving of the fronts of FRIS and Ross Ice Shelf.) The winters are extremely cold and the sea is perennially ice covered. Much of the wintertime ice production occurs at the front of FRIS, where offshore winds and tidal motion continually remove new ice, leaving the sea exposed to the frigid air. When ice forms from seawater, most of the salt is left behind in the water. The high ice-production rates in the southern Weddell Sea thus produce very salty water that has a temperature equal to the surface freezing point. This dense water flows to the deepest parts of the continental shelf, beneath the ice shelf. The main flow into the cavity follows Ronne Depression, because the saltiest (i.e., densest) water forms at the western end of the ice front. This inflow supplies most of the heat for basal melting of the thickest ice. The resulting "ice pump" causes freezing beneath thinner ice and an outflow of Ice Shelf Water (ISW) to the east of Berkner Island in Filchner Depression. The ISW fills much of Filchner Depression and overflows at the northern end, from where it flows down the continental slope to form Antarctic Bottom Water.

Filchner Ice Shelf was the planned starting point for early attempts at traversing the Antarctic continent by expeditions led by Wilhelm Filchner (1911–1913), Ernest Shackleton (1914–1917), and Vivian Fuchs (1957–1958). The last, successful expedition was contemporaneous with oversnow traverses of both Filchner and Ronne ice shelves that formed part of the United States programme for the International Geophysical Year. Since then, mapping of ice shelf extent and thickness has been completed by airborne radar sounding and satellite remote sensing. Water column thickness beneath the ice shelf has been mapped by seismic sounding. Ice flow has been measured by ground surveys and recently by satellite remote sensing. The picture that has emerged is one of near equilibrium. The rapid changes that have been observed on other ice shelves are not seen on FRIS. This is probably because its extreme southerly location buffers it from the effect of rising air temperatures seen further to the north. While the atmosphere remains cold enough to prevent surface melting and sustain the production of sea ice at the ice front, the processes of mass gain and loss are likely to stay largely unaltered. However, to confirm this requires a greater understanding of the processes than we currently have. Recent research on FRIS has been aimed at addressing these deficiencies, primarily through studies of the inflowing ice streams and of the ocean circulation beneath the ice shelf.

ADRIAN JENKINS

See also **Antarctic Bottom Water; Antarctic Ice Sheet: Definitions and Description; Continental Shelves and**

Slopes; Glaciers and Ice Streams; Ice Shelves; Icebergs; Polynyas and Leads in the Southern Ocean; Ross Ice Shelf; Sea Ice: Types and Formation; Weddell Sea, Oceanography of

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FILCHNER, WILHELM

Wilhelm Filchner was born on September 13, 1877 in Munich, son of Eduard and Rosine Filchner. As a teenager he enrolled in the Munich Cadet Corps, the first step in a military career. Having gained official Russian approval, in 1903 he undertook his first expedition: a solo trip on horseback across the Pamir Mountains from Osh in the Fergana Basin to Murgab, then back via Kasgar in Sinkiang.

This led in turn to his first scientific expedition, to map the upper course of the Ma-Qu (Huange He) in western China for the first time. Now with the rank of lieutenant, he set off for China in the fall of 1903 and returned home early in 1905, having accomplished his mission, despite some terrifying encounters with the hostile Ngolok tribe. Thereafter he worked at the Trigonometrical Department of the Prussian Land Survey, instructing route-surveying courses for officers posted to the German colonies.

In the light of endeavors by Belgium, France, Britain, Japan, Sweden, and Australia in exploring Antarctica, Filchner was motivated to plan his own Antarctic expedition. With the support of his superiors in the German Army, he proposed crossing the Antarctic Ice Sheet from the Weddell Sea to the Ross Sea, using sledges drawn by ponies. In preparation for this expedition, he mounted a small practice expedition to Svalbard in the summer of 1910.

The expedition headed south in 1911, entering the Weddell Sea in December of that year. Due to bad luck and serious opposition from the captain of the expedition vessel, *Deutschland,* Filchner was unable to establish a foothold on the continent. *Deutschland* became beset in the ice of the Weddell Sea early in 1912 and spent the winter adrift. Fortunately she emerged unscathed. Positive accomplishments included the exploration of the east shore of the Weddell Sea (Luitpold Coast) and the discovery of the Filchner Ice Shelf.

With the outbreak of World War I, Filchner spent some time on the Western Front, then was transferred to the Intelligence Service of the German Admiralty and was appointed head of the Naval Intelligence Service in Norway and later in The Hague.

For several years after the War, he supported himself by writing, about both Sinkiang and the Antarctic. Then, between 1926 and 1937, he mounted two major expeditions to Sinkiang and Tibet, whereby he completed impressive geomagnetic traverses of some 6500 and 3500 km, respectively, often living and traveling under extremely difficult conditions and suffering various injuries and bouts of illness. It was on this basis that he was awarded the Nationalpreis für Kunst und Wissenschaft by Adolf Hitler on January 30, 1938.

When World War II broke out in the fall of 1939, Filchner was engaged in geomagnetic surveys in Nepal, where he contracted malaria. On heading south for treatment, he was interned when he crossed into India, and spent the war years, with his daughter Erika, in the ladies' camp at Satara, near Poona.

At the end of the war Filchner opted to stay in India, settling in Poona. Finally, in 1949, ill health obliged him to return to Europe, where he settled in Zürich. He died on May 7, 1957, at the age of 79, and was buried in Enzenbuhl Cemetery in Zürich.

William Barr

See also **German South Polar *(Deutschland)* Expedition (1911–1912); Weddell Sea, Oceanography of**

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FILM

Antarctic film can conveniently be thought of as spanning a number of genres and fulfilling a variety of requirements, both for the filmmakers and their various audiences. Antarctic films have appeared as newsreels, pictorial expedition diaries, technical films recording discoveries (such as new land or flora and fauna), documentaries, and fictional stories about Antarctic explorers, their exploits, and their expeditions. Inevitably many Antarctic films cross these boundaries, falling into one or more categories.

In 1904 an anonymous member of the Scottish National Antarctic Expedition first made motion pictures of the Antarctic. British Antarctic explorers were quick to adopt motion picture making as an important and legitimate expedition tool as they quickly realised the power and importance of the new medium. The earliest films, like Herbert Ponting's (1870–1935) *90° South* (1914) (his film of Scott's final expedition); Frank Hurley's (1885–1962) *Dr. Mawson in the Antarctic/Home of the Blizzard* (1913) (documenting Mawson's Expedition [1911–1914]) and Hurley's *South* (1919), which chronicled Shackleton's *Endurance* Expedition (1914–1916), were extraordinary achievements. These beautifully crafted films were achieved under appalling conditions for men and equipment as the mechanisms in early hand-cranked movie cameras frequently became unworkably stiff in very low temperatures, lubricants became viscous, lenses "fogged" and "sweated," and snow somehow invaded even light-tight cameras.

The scope of these early films ranged far beyond popular entertainment, as they afforded their audiences the opportunity for vicarious participation in the process and exploits of exploration, which were often staged for the camera. Film provided a medium whereby the public was invited, at a distance, to witness and verify the priority and territorial claims of Antarctic explorers. Crucially, they also coincided with the beginning of the newsreel's heyday. Pioneered by Pathé Frères, the weekly "Pathé Journal" began in Paris in 1909/1910. It was quickly followed by their English "Animated Gazette," which was projected to an estimated audience of over two million, any one of whom could be a potential sponsor for the often cash-starved future Antarctic expedition.

By 1928 film was an indispensable tool for exploration in a year that was seminal for filmmaking in the Antarctic. While Richard E. Byrd's media-savvy expedition was closing in on the Ross Ice Shelf with cameramen Willard Van Der Veer and Joseph Rucker of Paramount News, Sir George Hubert Wilkins and Carl Ben Eielson were filming undiscovered land on their historic flight, the first to utilise film and the aeroplane to facilitate territorial discovery in the Antarctic. While Antarctic filmmaking variously served the purposes of documentary record, publicity vehicle, and cartographical aide-memoir, the versatility of the medium prompted a rueful Byrd to "regret" that on his 1925 expedition he had "paid little attention to motion pictures" or to "Donahue, of Pathé" to whom he had not "give[n] much time and attention."

In the post-WW II era film acquired a strategic value for military planners with films like *The Secret Land* (1948), which chronicled the US Navy's strategic Operation High Jump. By the 1940s the Antarctic was also providing imaginative material for the film industry with films like Charles Frend's 1948 *Scott of the Antarctic,* a dramatic reconstruction of Scott's last expedition scored by Ralph Vaughn Williams. In more recent years *Mr. Forbush and the Penguins* (1971) and *Conquest of the South Pole* (1988) have perpetuated the image of Antarctica as an escape from everyday life, while documentaries on Antarctic discovery like *Icebound (100 Years of Antarctic Discovery)* (1994) and a plethora of documentaries and films on Shackleton continue to explore the myth of the Antarctic explorer.

Ian N. Higginson

See also **British Antarctic *(Terra Nova)* Expedition (1910–1913); Byrd, Richard E.; Imperial Trans-Antarctic Expedition (1914–1917); Mawson, Douglas; Scott, Robert Falcon; Shackleton, Ernest; Wilkins, Hubert**

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FIN WHALE

The fin whale is order Cetacea, suborder Mysticeti (meaning moustache, which refers to baleen plates), family Balaenopteridae, and genus and species *Balaenoptera physalus* (Linnaeus 1758). Other common names used include "finback," "finner whale," "razorback," and "common rorqual." Despite the prevalence of references to "fin," it is interesting to note that the dorsal fin of the fin whale is less pronounced than that of the sei *(B. borealis)* or the Bryde's *(B. edeni)* whale.

General Appearance and Size

Fin whales are the second longest of the great whales. In the Southern Hemisphere, females average about 21–22 m in length and weigh around 60–80 tonnes. Females are generally about 5% longer than males. The largest animals can reach up to 26 m.

The slender fin whale has a narrower head than the blue *(B. musculus)* whale, with a single well-defined head ridge running to the paired blowholes. The fin whale can be identified by its asymmetrically coloured head. The dark grey colour characteristic of the rest of the dorsal surface reaches down further on the left-hand side than the right. The right-hand side, including the lip, is a creamy white colour. This is also true of the front 20%–30% of the baleen plates. The skin shows little mottling (although it is sometimes covered in pale oval scars thought to be caused by lampreys or remoras). The ventral surface is white. The dorsal fin is falcate and set about three-quarters back on the body. Fin whales are rorquals and have 55–100 ventral grooves that run from the lower jaw to the umbilicus and that allow the mouth to expand when feeding. They have 350–400 triangular baleen plates hanging from the upper jaw on each side (about 0.7 m in length and 0.3 m at the widest part), spaced 1–3 cm apart, used in filtering krill. The flippers reach about 15% of body length and are dark grey on top and white underneath, as are the broad flukes.

In Antarctic waters, all or portions of the body may have a dark yellow-green to brown sheen from the presence of diatoms.

Distribution and Migration

Fin whales are found throughout the Southern Hemisphere (and, indeed, the Northern Hemisphere). They migrate between subtropical breeding areas (although the location of the breeding grounds is unknown) and their Antarctic feeding grounds, which appear to be related to the Polar Front, most fin whales being found between around 55°–62° S (i.e., just south of the Polar Front). Like the other large whales, fin whales rarely feed outside the Antarctic, and so in the 4 months (December to March) they spend in the Antarctic they must store energy in their blubber to last them for the migration to and from the breeding grounds as well as the time spent on the breeding grounds. Although detailed information on population structure is lacking, there are probably at least six separate populations of fin whales in the Southern Hemisphere.

Life History and Behaviour

Fin whales can live to be 100 years old. They reach sexual maturity at around 20 m (females) and 19 m (males) when they are 8–10 years old. The gestation period is thought to be around 11 months; newborn calves weigh 1–1.5 tonnes and measure around 6 m. They are weaned at about 6 months, by which time they have reached 11–12 m. There is some evidence that pregnancy rates increased and animals reached sexual maturity earlier as a result of whaling, perhaps as more food per individual became available.

Little is known about the social structure of fin whales. They are usually seen as single animals or in small groups of two to seven, although larger concentrations (up to fifty animals) are known in areas of high prey density. Their primary prey is a species of krill, *Euphausia vallentini*. Fin whales can engulf vast quantities of water and prey with their ventral grooves fully distended and eat up to 1–2 tonnes of krill per day. Fin whales typically dive for around 8–12 minutes and to depths of 100–200 m when feeding. Fin whales are relatively fast swimmers, with normal travelling speeds of around 4–5 knots with short bursts of as much as 18 knots occurring if chased.

Conservation/Status

Reflecting their size, fin whales were the second most preferred target of commercial whalers in the Antarctic after blue whales. About 682,000 were killed south of 40° S between 1904 and 1975, with over half of these killed between 1947 and 1961. They have been protected in the Southern Hemisphere since 1976.

Although still at very low population levels (perhaps less than 10% of their original numbers), there is some evidence that fin whales are recovering in some areas. A recent study estimated their numbers south of 60° S in the Antarctic to be at least 5500 in 1996.

Aside from man, the main predator of fin whales is the killer whale, *Orcinus orca,* which has been known to take adults as well as calves. Possible interspecific competition has been postulated with other baleen whales. The effect of climate change on stocks of krill and hence fin whales is unknown.

Rob Williams and Greg P. Donovan

See also **Diving—Marine Mammals; International Whaling Commission (IWC); Killer Whale; Polar Front; Whales: Overview; Whaling, History of; Zooplankton and Krill**

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FINLAND: ANTARCTIC PROGRAM

Finland started active research in the Antarctic in 1988 when the research station Aboa was established. Aboa is situated in Queen Maud Land, about 130 km inland from the Weddell Sea on the nunatak Basen in the Vestfjella Mountains. Aboa is occupied only during the Antarctic summer. The Swedish research station Wasa is located 200 m from Aboa and the stations cooperate in research and logistics.

The Antarctic organizations in Finland are divided under several ministries. The Ministry for Foreign Affairs is responsible for handling issues related to the Antarctic Treaty System. The Ministry of Environment is involved in the Committee for Environmental Protection (CEP) and permissions. The Ministry of Education leads the Coordination Committee for Antarctic Research, the purpose of which is to promote the cooperation of different authorities, to establish the priorities for Finnish Antarctic research and to supervise the logistics of expeditions. The Academy of Finland (the Research Councils) is mainly responsible for the financing of Antarctic research projects, although some governmental research institutes have projects funded by their budgets. The logistical support is provided by the Finnish Antarctic Research Program (FINNARP), hosted by the Finnish Institute of Marine Research.

The scientific National Committee for Polar Regions Research (National SCAR Committee) deals with both Arctic and Antarctic research. There has been close cooperation with several other countries, including Argentina, Norway, Russia, South Africa, and Sweden. A number of Finnish projects have contributed to large-scale international programmes and several projects expect to participate in the International Polar Year 2007/2008 programmes.

The Antarctic research in Finland had started already prior to the establishment of the Aboa station (i.e., the Institutes of Meteorology of Finland and Argentina established a cooperation in ozone research in 1987). The first Finnish Antarctic expedition visited Aboa during the southern summer of 1989/1990 and during the 1990s the research activity expanded and became more diversified. The enlargement and development of Aboa become necessary, and from 2002–2004 more working and accommodation space was built, including more energy-saving and environmentally friendly facilities and new power supplies for all-year automated instruments.

The main activities of the Finnish Antarctic research and the field expeditions are concentrated in Queen Maud Land and the Weddell Sea. The main research fields are oceanography and marine biology, meteorological studies, geology, geophysics, and geodynamics. Current research projects include a geochemical and isotopic project on lithospheric evolution of Dronning Maud Land and hydrogeological research; paleoclimate studies on Antarctic Blue Ice Fields; glacial history and paleoceanography; seasonal snow studies in Antarctica; Antarctic UV and ozone monitoring and mesoscale atmospheric studies; sources, transformation, and characteristics of Antarctic aerosol; air–sea–ice interaction in the Antarctic Seas; and GPS and absolute gravity measurements for geodynamics studies.

Institutes participating in the Antarctic research include several departments and research units in the University of Helsinki, University of Oulu, University of Lapland, Finnish Institute of Marine Research, Finnish Meteorological Institute, Finnish Geodetic Institute, and Geological Survey of Finland.

Markku Poutanen

See also **Antarctic: Definitions and Boundaries; Antarctic Treaty System**

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FIRN COMPACTION

Firn compaction, or firnification, is the process by which an initial loose aggregation of snow particles compacts into solid glacial ice. Firn is snow that has survived at least one complete annual cycle, for example, along the northern part of the Antarctic Peninsula, implying persistence through a melt season. Freeze–thaw processes enhance firn compaction rates. Most of the high vast Antarctic polar plateau, however, is a dry snow zone, where no melting occurs, so firnification there is a subtle progression over many years and hundreds of metres through the snowpack.

Snowflakes deposited on the surface have a variety of forms depending on the atmospheric conditions under which they grew. Temperature determines geometry, while humidity dictates size. In cold, dry Antarctic air, snowflakes are mostly simple needles, columns, and plates, with occasional classic stellar dendrites (star-shaped with fern-like branching). These pack loosely together, so a layer of freshly fallen snow formed in calm conditions has a bulk density of only 25% that of water. Within a few days of settling, surface winds jostle neighbours into a close-packed arrangement of fine-grained old snow.

Snow is an excellent insulator, so temperatures a few metres down in the pack are practically independent of the daily and seasonal variations taking place at the surface. Firnification is therefore sometimes called equitemperature metamorphism. In the initial stages it is dominated by vapour transport through the process of sublimation (from or to a solid directly to or from a vapour, without melt). This rearranges the original snow particles, minimising the ratio of surface area to volume, by redistributing molecules from one part of a crystal to another. The process results in an assemblage of rounded grains, the larger of which grow at the expense of the smaller ones. Continued settling, wind compaction, and initial bonding together of rounded grains increases bulk densities relatively rapidly to around 55% that of water, at depths between 10 and 30 m.

As more snow accumulates, the added weight applies, increasing overburden pressure to the layers below. This results in individual crystals slowly deforming and sintering together to gradually reduce the interconnected air channels between them into discrete bubbles. When most pores have been confined to bubbles in the ice matrix, the density has reached 83% that of water, and transformation to glacier ice is complete. This level is called the firn–ice transition, and in Antarctica it occurs at depths ranging from 50 m near the coast to 120 m far inland. Surface air, which mixes freely through the firn, cannot penetrate beyond this depth. Further compression of glacier ice at great depth increases the air pressure in the bubbles, reducing their volume, eventually squeezing the bubbles into the ice crystal lattice, with final densities of 92% that of water.

Firnification rates depend on many factors. In Antarctica they are influenced by high winds accelerating initial compaction stages, but dominated by very low temperatures and minimal accumulation (snowfall), which result in protracted densification that may see complete transformation to glacial ice taking well over 1000 years (e.g., Vostok).

Mike Craven

See also **Air-Borne Ice; Air Hydrates in Ice; Antarctic Ice Sheet: Definitions and Description; Atmospheric Gas Concentrations from Air Bubbles; CryoSat; Glaciers and Ice Streams; Ice–Atmosphere Interaction and Near-Surface Processes; Ice Core Analysis and Dating Techniques; Ice Sheet Mass Balance; Ice Sheet Modeling; ICESat; Mega-Dunes; Paleoclimatology; Precipitation; Snow Chemistry; Snow Post-Depositional Processes; Surface Energy Balance; Surface Features; Temperature; Vostok Station; Wind**

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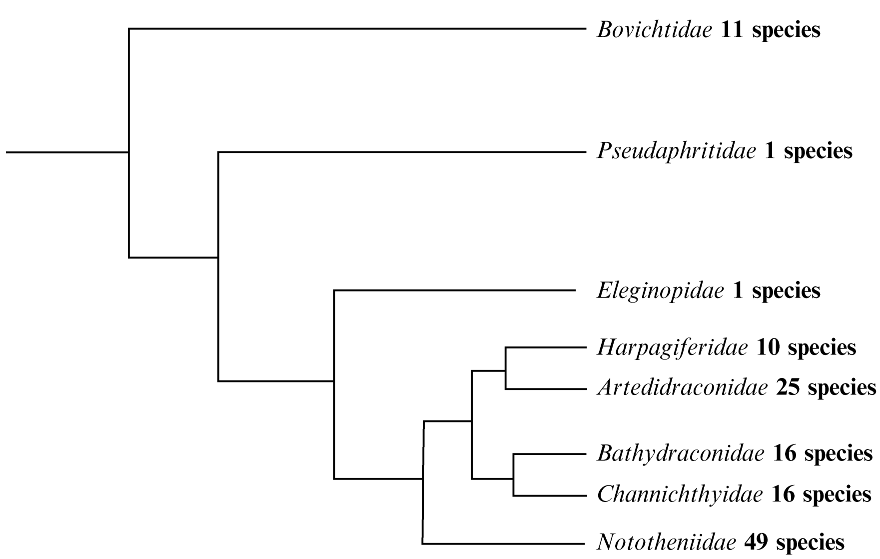
FISH: OVERVIEW

During the past 40 million years, on the Antarctic shelf there has been a nearly complete replacement of the cosmopolitan temperate ichthyofauna (fish) from the late Eocene by the highly endemic (up to 97%), cold-adapted modern fauna. The suborder Notothenioidei (order Perciformes) is dominant in species number and biomass, and to date is the most thoroughly characterised fish group of the world.

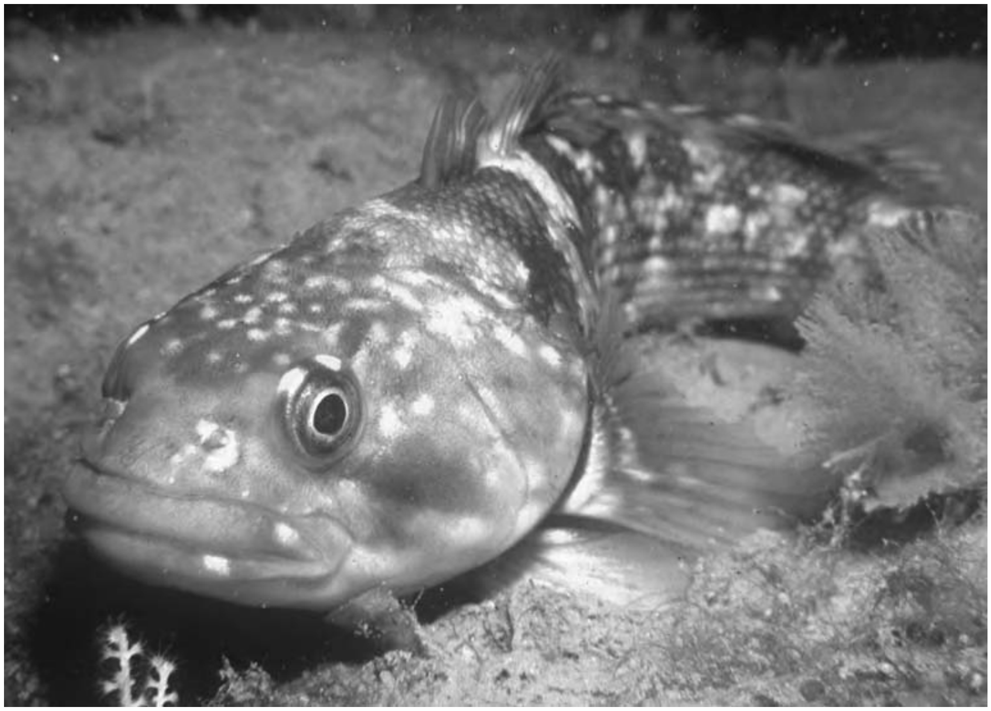
During the progressive geographic isolation, the physiology of Antarctic fish became gradually adapted to the cooling of the habitat. Thanks to adaptation, they are comfortable only in the cold, where their metabolism works best. Antarctic fish are stenothermal, such that raising the water temperature just a few degrees centigrade can cause their death. Coastal Antarctic waters, where survival of temperate fishes would be impossible due to freezing, are at –1.87°C, the equilibrium temperature of seawater and ice, for much of the year. The Polar Front has become a natural barrier to migration in both directions, fulfilling an essential role for evolution in isolation. The capacity to adapt is variable. Highly stenothermal organisms may not tolerate temperature changes of 1°C–2°C. Arctic fish, however, have adapted to survive over a wider thermal range.

In recent years, studies of the evolutionary history of Antarctic fish have envisaged coordination and stimulation of research on evolution in response to climate change, gradually extending to the Arctic scenario. During the Cenozoic, tectonic and oceanographic events played a key role in delimiting the two polar ecosystems and in influencing the evolution of their faunas. The Antarctic has been isolated and cold longer than the Arctic, with ice-sheet development preceding that in the Arctic by at least 10 million years. Although Antarctica and the Arctic have high latitudes and cold climates in common, the two regions are more dissimilar than similar. Due to the Polar Front, the climatic features of the Antarctic waters are more extreme and constant than those of the Arctic.

The modern polar faunas have lower taxonomic diversity than at low latitudes, possibly resulting from lower evolutionary rates at the poles. However, they differ in age, endemism, taxonomy, zoogeographic distinctiveness, and range of physiological tolerance to various environmental parameters. There are



Notothenioid phylogeny at the family level.



Nototheniid, *N. rossii,* sitting on the sea bed at a water depth of 10 m. (Courtesy of David K. Barnes.)

advantages in using organisms from both poles in evolutionary studies. Some fish families (e.g., Zoarcidae and Liparidae) are represented in both polar oceans; however, hypotheses of adaptation to a common environmental parameter are better supported when a feature can be compared in distantly related taxa from both habitats, allowing examination of convergent/parallel evolutionary trends. Pertinent examples include the convergent evolution of the identical antifreeze glycoproteins of southern notothenioids and northern cods, and the recently found divergence of Arctic hemoglobins from those of Antarctic notothenioids (see following discussion).

Example 1: Antifreeze Compounds

The biosynthesis of antifreeze (glyco)proteins and peptides (AFGPs, AFPs), which allows polar fish to tolerate temperatures as low as –1.9°C, is a most intriguing evolutionary adaptation, and meets the criteria for a "key innovation." Antarctic fish must rely on this adaptation throughout the year, whereas in Arctic fish, biosynthesis of AF(G)Ps occurs only in the coldest winter months. Most of our knowledge on freezing avoidance comes from more than three decades of studies by Arthur L. DeVries's team.

In Antarctic notothenioids, the AFGP gene evolved from the gene of an enzyme (a trypsinogen-like protease), which provided the front and tail of the AFGP gene (Cheng 1998). The finding in the notothenioid genome of (i) a chimeric AFGP-protease gene intermediate, (ii) a protease gene still bearing the incipient coding element, and (iii) independent AFGP genes reveals a fascinating case of "evolution in action." The genome of a phylogenetically unrelated Arctic fish, the polar cod *Boreogadus saida* (family Gadidae), contains AFGP genes that encode nearly identical proteins. This would suggest a common ancestry. On the contrary, the genes of the two fish groups are not homologous, and hence have not followed the same evolutionary pathway. Assuming an endogenous, yet unknown genetic origin, the cod AFGP genes have evolved from a different, not trypsinogen-like, genomic locus. An example of convergent evolution has thus been discovered.

Example 2: Oxygen Transport

There has been a major evolutionary pressure for fish to adapt and modify the functional features of haemoglobin (Hb). Located in the blood erythrocytes, Hb has two pairs of identical α and β globins; its structure is indicated as $\alpha_2\beta_2$. Each globin contains the heme group, whose Fe++ ion binds oxygen during respiration. Oxygen is carried along capillaries by one or more Hbs, and released to tissues according to the metabolic needs.

Antarctic fishes show adaptive reductions in Hb content/multiplicity and erythrocyte number, which counterbalance the higher demand of energy for circulation caused by increased blood viscosity produced by subzero temperatures of sea water. Low temperatures reduce the metabolic demand for oxygen while increasing its solubility in the blood, so that more oxygen can be carried in physical solution, and less needs to be bound to Hb.

One notothenioid family (the only known adult vertebrates showing such an astonishing adaptation) has abolished Hb as oxygen carrier. The colourless blood of the "icefishes" (family Channichthyidae) lacks Hb and erythrocytes. Compensatory adaptations enhancing oxygen delivery include large gills, scaleless and highly vascularised skin, large capillary diameter, and a large increase in cardiac output and blood volume. They maintain normal metabolic function by carrying oxygen physically dissolved in the blood. Icefishes retain a small, inactive portion of adult α-globin gene(s) and no detectable β-globin gene(s) as a result of a single deletion in the ancestral channichthyid genome, which removed almost the entire notothenioid globin-gene complex. Why have Channichthyidae taken such a radical course, leaving the other families with only partial Hb reduction? The physiological role of Hb in oxygen transport in temperate and tropical fish is undisputed; however, does Hb remain vital for adequate oxygen transport in the Antarctic red-blooded families, or is it a redundant vestigial relict? The answers were found by reversibly "poisoning" Hb of the red-blooded nototheniid *Trematomus bernacchii* with carbon monoxide. This gas causes death to organisms (such as any temperate fish) whose lives depend on oxygen, because it replaces oxygen in Hb, blocking transport. However, no signs of distress, even during enforced exercise, were observed in the experimental fish *(T. bernacchii)*. The survival of *T. bernacchii* despite Hb incapacitation, leaves little doubt that, in the cold, stable environment of the Antarctic seas, routine oxygen delivery is possible also in the absence of functional Hb. Similar to icefish, red-blooded Antarctic fish can carry routinely needed oxygen dissolved in the blood.

The capacity of fish to colonise a large variety of habitats is strictly related to the molecular and functional differences encountered in their Hbs. Seven of the eight notothenioid families are red blooded. Most are sluggish bottom dwellers and show reduced Hb multiplicity, consisting of a single Hb (95%–100% of the total). Multiplicity is considered to be linked to lifestyle and environment variability; that is, in highly variable environments active fishes need a higher number of Hbs. The lifestyles of three species (active, cryopelagic *Trematomus newnesi* and *Pagothenia borchgrevinki;* and *Pleuragramma antarcticum,* a pelagic, migratory fish) are different, and their oxygen-transport systems are adjusted to each lifestyle. Multiplicity is higher (three to five functionally distinct Hbs).

Several notothenioids thrive in non-Antarctic waters, and provide important evolutionary information. Eleven out of twelve species of Bovichtidae and Pseudaphritidae, the most primitive families, live in temperate waters. *Pseudaphritis urvillii,* common in Australian rivers, has never developed cold adaptation; however, the amino-acid sequences reveal higher identity with Hbs of Antarctic notothenioids than with any temperate fish, but at the low limit of the percentage range. This argues in favour of a common origin within notothenioids, but also suggests divergence during early cooling, before the event that gave origin to AFGPs.

Some haematological parameters (high erythrocite number and Hb content) of non-Antarctic *Notothenia angustata* favour oxygen transport in a temperate environment; but Hb multiplicity and structural/functional features closely resemble those of Antarctic notothenioids. *N. angustata* appeared well before the Polar Front. However, at the end of the Miocene (5 Ma), the Polar Front moved northwards up to 39° S, the latitude of northern New Zealand, facilitating migration. The genome contains silent antifreeze genes, which can be activated by acclimation to low temperatures, indicating that—unlike *P. urvillii*—*N. angustata* was cold adapted prior to migration to temperate latitudes.

Arctic fish Hbs are increasingly becoming familiar. The benthic spotted wolffish *Anarhichas minor* (family Anarhicadidae) and three Gadidae (the benthic Arctic cod *Arctogadus glacialis,* the pelagic and migratory polar cod *Boreogadus saida,* and Atlantic cod *Gadus morhua*) all have Hb systems whose structural and functional features are remarkably different from those of the phyletically unrelated Antarctic species. They all have three Hbs, probably in response to the need to optimally adapt to the Arctic waters.

Example 3: Molecular Evolution

Investigation of individual genes using molecular methods is a powerful new aid in evolutionary biology and ecology. Molecular phylogeny is also essential for studying evolution, using protein (e.g., Hb) and nucleic-acid sequences, and chromosome change.

The amino-acid sequences of Hbs of polar and temperate fish have been analysed by means of computer programmes. A phylogenetic tree shows that *P. urvillii* and *Cottoperca gobio* (family Bovichtidae) diverged before the formation of the Polar Front, and that temperate *N. angustata* Hb groups with Antarctic nototheniids, supporting the hypothesis that it was cold adapted prior to migration.

The most important indication from molecular phylogeny is the divergence of Arctic Hbs from notothenioid Hbs. The constant physicochemical conditions of the Antarctic seas are matched by clear grouping, whereas Arctic Hbs occupy scattered positions between Antarctic and temperate groups, in keeping with the variability in the latitudinal gradient in which the Arctic species live, and their often active, pelagic, and migratory lifestyles. Distinct evolutionary pathways of the respiratory system have been driven by the need to adapt to different environmental constraints. It is not surprising that the Arctic ichthyofauna, which is not dominated by a single, taxonomically uniform group, has high phylogenetic diversity.

Future Perspectives

Antarctica is not widely considered one of the notable evolutionary sites (e.g., the East African Great Lakes, Lake Baikal, the Galapagos), perhaps because research has emphasised aspects of extreme biology rather than unifying principles of evolutionary biology. In order to survive, Antarctic organisms had to overcome strong constraints. Uniquely adapted to an extreme, isolated, and constant environment, the biota is highly susceptible to changes. In a world attuned to changes in global climate and to threats of loss of biodiversity and depletion of fisheries, the study of adaptations will provide invaluable clues to the organism response to environmental changes, particularly human induced (global warming and increased UV due to ozone depletion). Antarctic fish have been and will continue to be a key element in investigating and probably establishing the Southern Ocean as a centre of evolution.

Climate change can affect every aspect of an organism's biology, from cellular physiology and biochemistry to food web and habitat. Coping with changes in enzyme activity and DNA damage, organisms evolve phenotypic responses (occurring within the lifetime and including enzyme activation/inhibition and induction/repression of gene regulation), and genotypic responses (occurring over a much longer timescale through selection of beneficial mutations). Arising through errors in DNA replication, genotypic responses may be accelerated by increased UV radiation, which places additional demands on DNA repair, giving greater opportunity for errors.

In summary, it is necessary to study evolutionary processes in response to selection pressures associated with global change (in collaboration with the physical sciences community), evolutionary response across the molecule-to-species range of organisation (utilising molecular and biochemical techniques integrated with taxonomy, physiology, ecology, ethology, and morphology), changes in the physical environment that have driven evolution over geological time (in collaboration with the palaeosciences community), and statistical and molecular genetic approaches to analyse the biodiversity of the modern polar fauna and flora. Antarctic/Arctic comparisons are important, because the differences in the two polar environments are differently reflected in global climate changes. Accordingly, studies on their ecosystems are likely to provide answers to different questions, often complementary to one another.

The role of the polar habitats in global climate changes has awakened great interest for the evolutionary biology of its organisms. Great difficulties are to be expected in tackling the topic of evolution. However, in the fertile scenario of polar biological research, this is an exciting challenge.

GUIDO DI PRISCO and CINZIA VERDE

See also **Climate Change; Pelagic Communities of the Southern Ocean; Polar Front; Southern Ocean; Toothfish**

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FISHERIES AND MANAGEMENT

Interest in fishing in the Antarctic was first shown by the Soviet Union in the early 1960s, and by 1966/1967 the USSR had established a fishery for the marbled rockcod, *Notothenia rossii,* around the sub-Antarctic island of South Georgia. This fishery peaked in 1969/1970 with a reported catch of 400,000 tonnes, but by the 1971/1972 split year the fishery was severely depleted. In 1971 the fleet turned its attention to a new sub-Antarctic fishing ground, at Kerguelen Islands in the Indian Ocean. The fishery for rockcod lasted longer at Kerguelen than at South Georgia, but by the 1980s this stock too had been severely depleted.

Fisheries for a second species, mackerel icefish *(Champsocephalus gunnari),* also developed in the early 1970s, at both Kerguelen and South Georgia. Catches were highly variable from year to year, and icefish stocks declined severely in the 1990s, for reasons that seem not to be due to fishing. At South Georgia there has been a sufficient recovery of icefish for a small, tightly regulated fishery to take place since the late 1990s. In the mid-1990s a fishery for icefish developed at Heard Island and McDonald Islands, south of Kerguelen but on the same plateau. In 2003, Australia, Chile, the Republic of Korea, and the UK fished for icefish.

In addition to the two primary species, rockcod and icefish, fisheries in the 1970s expanded to take other species—*Notothenia squamifrons, Patagonotothen guntheri, Pseudochynichthys georgianus, Chaenocephalus aceratus,* and *Chaenodraco wilsoni*—from South Georgia and Kerguelen, and from other areas such as the Antarctic peninsula, the South Orkneys, and the Indian Ocean sector close to the continent. None of these areas or species proved to be sufficiently productive to sustain major fisheries and most are now closed. The Soviet Union was joined by other countries, so that by 1977/1978, Bulgaria, Chile, the German Democratic Republic, Japan, and Poland were also catching fish in Antarctic waters.

The next major fishery to develop was for krill *(Euphausia superba)*. The great abundance of Antarctic krill, the primary food of the baleen whales, had been known about since the early twentieth century. Part of the Soviet Union's exploration from the early 1960s was directed at finding methods of catching and processing krill, but catches remained small until a permanent krill fishery was established in the Southern Ocean in 1972. Full-scale operations were underway in 1973 when a Japanese fleet also started fishing. Both nations were producing krill products for human consumption, as whole canned tails, whole frozen krill, or krill paste. Catches of krill by the Soviet fleet in Antarctic waters increased rapidly in the late 1970s, and a number of additional countries also started fishing, notably Poland, Chile, and the Republic of Korea. Catches of krill reached a peak of 528,201 tonnes in 1981/1982 and have since declined. Initially the decline was due to processing difficulties, since krill have high levels of fluoride in their shells, and most krill caught today are processed either into fish-meal principally as an aquaculture feed or frozen for use as bait in sport fishing.

Early Soviet research had identified a number of areas of high productivity and krill abundance around Antarctica. However, only the three areas in the South Atlantic (the South Shetlands, South Orkneys, and South Georgia) have proven to have krill in swarms dense enough and in predictable areas for sufficient periods of the year to make fishing economic. The final decline in krill catches came with the breakup of the Soviet Union. In 1989/1990 the Soviet Union took 326,000 tonnes of krill, and by 1993/1994 this had dropped to 13,000 tonnes, taken by ex-Soviet vessels now flagged to Ukraine. Current fishing nations are Japan, Korea, Poland, Ukraine, and the US.

In the 1990s a new type of fishery developed. Fishing had previously been carried out using trawl nets, either pulled along the sea floor (for rockcod and icefish) or in mid-water (for krill and sometimes for icefish). The new method used long lines with baited hooks attached, set on the sea floor to catch Patagonian toothfish, *Dissostichus eleginoides*. These fish are large and live in deep water, from 500 to 2000 m depth. They had been largely inaccessible to trawls, although some had been reported as by-catch in the fisheries for icefish during the 1980s. Once again fishing started around South Georgia and Kerguelen, but by the late 1990s this species was being caught around Prince Edward and Marion, Crozet, and Heard and McDonald Islands. A longline fishery for a closely related species, Antarctic toothfish, *Dissostichus mawsoni,* also started in the late 1990s in the Ross Sea. With the development of toothfish fisheries in the 1990s the number of fishing states rapidly increased. In 2003, Australia, Chile, France, Japan, New Zealand, Republic of Korea, Russian Federation, South Africa, Spain, the UK, and Uruguay all fished for toothfish.

Toothfish turned out to be very good quality fish, achieving a high market price. This high value, and the remote location of most of the fisheries, attracted large numbers of unlicensed fishing vessels. In the early 1990s, illegal, unregulated, and unreported (IUU) fishing, as it is called, took place around South Georgia, but from 1996 most IUU vessels moved to the Indian Ocean, fishing around Prince Edward and Marion, Crozet, Kerguelen, and Heard and McDonald islands.

Currently the only substantial fisheries in the Antarctic are Patagonian toothfish around several sub-Antarctic islands; Antarctic toothfish in the Ross Sea; mackerel icefish at South Georgia and Heard and McDonald Islands; and krill around the Antarctic Peninsula, the South Orkney Islands, and South Georgia.

When fishing started, in the late 1960s, there was very little legislation governing the areas where fishing took place in the Antarctic. In the early 1980s, two important international legislative instruments were agreed to that were to change this. In 1982 the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) came into force, with a remit to manage fishing in the Antarctic. Also in 1982 the United Nations Convention on the Law of the Sea (UNCLOS) was signed, with wide-ranging implications for fisheries worldwide. By 1992, when conservation measures for all krill stocks were agreed to by CCAMLR, all Antarctic fisheries were controlled.

CCAMLR's boundaries were defined to follow the Antarctic Convergence, where cold Antarctic water meets warmer northern water, because it is roughly the limit of Antarctic and sub-Antarctic ecosystems. Within this area several sub-Antarctic islands are under state sovereignty—South Georgia (UK), Bouvet Island (Norway), Prince Edward and Marion Islands (South Africa), Crozet and Kerguelen Islands (France), and Heard and McDonald Islands (Australia). Under the agreement of UNCLOS, these states can, and do, control activities within 200 nm of the islands—their EEZ or maritime zone. All these islands are north of 60° S. South of 60° S, Antarctic Treaty states have agreed to withhold from any activities that would exert their claims to territorial sovereignty, and since this includes the enforcement of 200-nm maritime zones, none of the waters south of 60° S are under state sovereignty. All waters outside areas of state sovereignty (the vast majority of Antarctic waters both north and south of 60° S) are termed "high seas waters," and come under the exclusive competence of CCAMLR with respect to fishing except with respect to whales and seals, which have their own conventions and are excluded from CCAMLR with respect to harvesting.

Although states have the right to deviate from the advice of CCAMLR within their sovereign sub-Antarctic island waters, in practice they generally implement CCAMLR decisions and recommendations. On the high seas within CCAMLR waters, CCAMLR members have the obligation to control the activities of their vessels in compliance with CCAMLR conservation measures, and the right to inspect vessels of another member. Nonparties (states that have not acceded to the convention and are not members of CCAMLR) are not bound by the provisions of CCAMLR. Nevertheless, although they have a legal right to fish, it is a feature of UNCLOS and later agreements, such as the UN Agreement on Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks, that they should not do so if this undermines the conservation activities of CCAMLR.

CCAMLR meets every October in Hobart, Australia—the location of the CCAMLR Secretariat—to agree on measures that should be implemented to conserve fish stocks. These may range from stock-specific measures, such as setting of catch limits, closed areas, and mesh sizes, to global measures, such as the toothfish Catch Document Scheme and lists of IUU vessels. The primary decision-making body, the Commission, is advised by a Scientific Committee and a Standing Committee on Implementation and Compliance (SCIC). These committees are themselves advised by specialist groups. The Scientific Committee receives advice on appropriate catch levels and other management measures, for finfish, crab, and squid, from the Fish Stock Assessment Working Group (WG-FSA). The Working Group on Ecosystem Monitoring and Management (WG-EMM) provides advice on krill catch levels and the state of the Southern Ocean ecosystem. SCIC analyses compliance by fishing vessels and the status of IUU fishing.

CCAMLR takes an "ecosystem approach" to managing all its resources—fish, squid, crabs, or krill. Fishing is undertaken in such a manner that it minimises the impact on nontarget species (the target species is the fish that the fisherman is looking for). For instance, albatross and petrels may be caught on longline hooks and drowned, but in CCAMLR, mitigation measures have been in place since the early 1990s that have reduced the number of birds killed in most Antarctic fisheries to negligible levels. There are limits on the quantity of nontarget species of fish and other animals that can be caught in all CCAMLR fisheries, to minimise the impact of fisheries on their populations.

The state of Antarctic fisheries is assessed using a variety of models, but in all cases catch limits are set to minimise the risk that the size of the stock will decrease to levels where the production of young fish might be impaired. Furthermore, depending on the place that a target species has within the Antarctic ecosystem, the fishery is managed so that there are sufficient animals left after fishing to supply predators with the food they need to survive. For instance, very many animals depend on krill—whales, birds, seals, fish, squid—so catch limits are set sufficiently conservatively to ensure that even after fishing, 75% of the original stock is still there for predators to eat. Toothfish are higher up the food chain, and fewer animals depend on them, so the appropriate level chosen by CCAMLR is to preserve 50% of the original stock.

Even with these conservative catch limits, the krill stock is so large that the catch limit is also large. The latest survey in the Atlantic (in 2000) showed that there were about 44 million tonnes of krill, and the relevant catch limit for the Atlantic is about 4 million tonnes. The catch limit for the Indian Ocean is 1 million tonnes. These figures are far in excess of the current catches of krill. Nevertheless, CCAMLR has a specific responsibility with respect to krill because it is such a key component of the Antarctic ecosystem. It has therefore developed the CCAMLR Ecosystem Monitoring Programme (CEMP), which is set up to monitor krill predators, to detect changes in their annual performance, and to determine whether these changes are due to natural causes or to the ecosystem effects of fishing. Up to fifteen indicators of performance are monitored for seven bird and seal species at sixteen sites around the Antarctic. The indicators range from small scale (foraging behaviour) to large scale (population size).

In an effort to combat IUU fishing, CCAMLR has put in place a Catch Document Scheme, in which each consignment of toothfish must be accompanied by a document stating that the toothfish were caught legally, and where and when they were caught, which stays with the consignment from the point of landing to the final point of import to a wholesaler. These documents are not available to IUU operators. CCAMLR has also developed a "black list" of vessels known to be involved in IUU fishing. Members with coastal state jurisdiction around sub-Antarctic islands have arrested, prosecuted, and sometimes sunk a large number of IUU vessels over the last 10 years.

CCAMLR also closely controls the development of new and exploratory fisheries, so that sufficient information is acquired about them before they are allowed to become large. The fishery for toothfish in the Ross Sea is currently an exploratory fishery. There are also exploratory fisheries for crabs and squid at South Georgia, but there is relatively little commercial interest in these at the present.

CCAMLR has a system of international scientific observation in which scientists from one member state can observe the fishing activities and measurements from the catch of another member. The data generated through this system are essential for the management of the fishery. All fishing vessels, except those involved in the krill fishery, must carry observers and operate a satellite monitoring system. Many fishing vessels also assist with scientific research.

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See also **Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Food Web, Marine; Squid; Toothfish; Whales: Overview**

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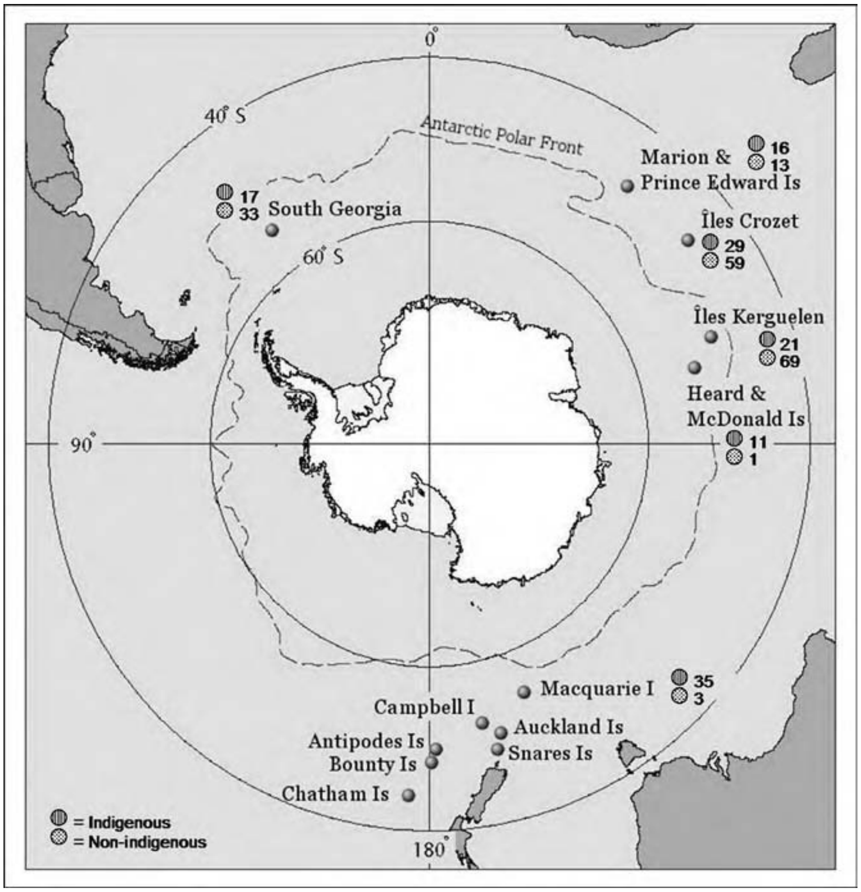
FLOWERING PLANTS

The history of flowering plants (angiosperms) in Antarctica is one of interaction between evolution, plate tectonics, long distance dispersal, and climate change. Well before the evolution of angiosperms, Antarctica was part of the supercontinent Gondwana, along with the current Southern Hemisphere continents and other land masses such as New Zealand, Madagascar, and India. Angiosperms had probably evolved in equatorial regions before the initiation of the Gondwanan breakup, some 180 Ma. Rapid expansion of angiosperms, however, corresponded with major phases in Gondwana's fragmentation. Some have suggested that intra-Gondwanan rift systems and newly created sea margins may have acted as corridors for dispersal of early angiosperms. Climate at the time was moist and cool and the high-latitude areas experienced extreme seasonal fluctuations in day length.

The interconnectedness or nearness of Gondwanan landmasses during the Cretaceous (144–65 Ma) coincided with evolutionary diversification in birds,



The number of native and nonnative angiosperm species recorded across the Antarctic region. (Indigenous numbers on top, nonindigenous numbers on bottom.) (Image source: The Australian Antarctic Division 2005.)

mammals, and angiosperms. The central position of Antarctica meant that it formed either the centre of, or the conduit for radiation of, many angiosperm lineages, including many fundamentally important Southern Hemisphere plant groups, such as the Myrtaceae and Proteaceae families and the iconic Southern Hemisphere genus *Nothofagus*. Gondwanan linkages through *Nothofagus* can be traced through extant species in South America and Australia, as well as through fossil remains in Antarctica.

The major angiosperm taxonomic order, Poales, appears to have evolved in what is now South America. Two major lineages developed; the sedges and rushes group (including Cyperaceae and Juncaceae), originating in west Gondwana (either South America or South Africa), and the grass group (Poaceae), originating in east Gondwana (Australia). This illustrates a significant point; as both groups are widely dispersed in all Gondwanan land masses today, but Africa had rifted apart early during angiosperm evolutionary time, over-ocean dispersal must have been an important biogeographic process.

The Cretaceous Antarctic environment included warm coastal areas, cooler interiors, and high carbon dioxide levels. To cope with the low angle of light, forests consisted of widely spaced, conical trees with vertically oriented leaves. Other more open vegetation types included coastal heaths, grasslands, and, with elevation, tundra and alpine zones. Fossil evidence from the Antarctic Peninsula indicates vegetation similar to present-day, cool Southern Hemisphere forests. Only plants adapted to winter darkness survived. For perennial plants, evolution selected for taxa in which carbon gain through summer photosynthesis was greater than carbon loss through respiration during winter. Some Southern Hemisphere extant tree species still possess the ability to survive long periods of darkness.

As India moved northward (132–43 Ma), it left a trail of underwater Gondwanan remnants, around which ocean sediments accumulated. This in association with volcanic activity created the mainly marine Kerguelen Plateau. The mid- to late Tertiary (25–5 Ma) saw coastal scrub-type vegetation, with ferns, grasses, and daisies on Heard Island as well as conifers on Îles Kerguelen.

By the middle of the Tertiary (38 Ma), all southern land masses had rifted apart from Antarctica. Once isolated from common ancestry, their angiosperm floras began to diverge towards unique floras. A circumpolar current flowing easterly around the Southern Ocean established between 35 and 28 Ma and Antarctica began to cool. With ice formation, habitats were lost, the treeline lowered, and ultimately, by 2.5 Ma, ice sheets had extended to the edge of the continental shelf of Antarctica and angiosperm-dominated plant communities had died out. Most plant species on the Kerguelen Plateau islands were also extirpated by glaciation; however, the regional endemic, the Kerguelen cabbage, *Pringlea antiscorbutica,* and the Kerguelen endemic cushion plant *Lyallia kerguelensis* may have survived in ice-free refugia.

Over the last one million years, the Earth has undergone cyclical cooling and warming. During this time, most sub-Antarctic islands were formed and colonized by plants through long distance, over-ocean dispersal. Today, sub-Antarctic islands experience cool, wet, and windy conditions and are clothed in treeless tundra. Major plant communities include tussock grasslands, herbfields, mires, and fellfields of scattered cushion plants and mosses. Long summer days and nutrient enrichment from marine animals provide conditions for high productivity on protected coastal areas. Fossil evidence from peats that accumulate on sub-Antarctic islands indicates that modern plant communities have been present for at least the last 10,000 years.

Currently there have been only fifty-five native angiosperm species from seventeen families found on the sub-Antarctic islands, two species from maritime Antarctica, and none from continental Antarctica. Important genera such as *Poa, Luzula,* and *Agrostis* also occur in Arctic communities. Some species have linkages with southern South America, and a considerable proportion of Macquarie Island's flora has affinities with the cool, temperate Campbell and Auckland islands, as well as New Zealand. The sub-Antarctic islands appear to be influenced by the same range of factors that influence ecology and biogeography elsewhere in the world. Vegetation complexity decreases with decreasing ambient temperatures, and variation in angiosperm flora size has been explained by island size, climate, and distance from neighbours. Similar reasons have been used to explain why only two species, a small grass, *Deschampsia antarctica,* and a small cushion plant, *Colobanthus quitensis,* have successfully colonized areas in the maritime Antarctic.

Two major issues concern Antarctic flora in the twenty-first century: global climate change, and the impact of nonindigenous (alien) invasive species introduced through human activities. The recent local colonization and rapid expansion of populations along the Antarctic Peninsula of *D. antarctica* and *C. quitensis* have been attributed to substantial warming in the region. Elsewhere, current research is documenting changes in the relative competitive ability of species due to different inherent responses to environmental change.

One hundred eight nonindigenous species from twelve families have been recorded from the Antarctic region. The impact of these species has been either direct or indirect and includes substantial loss of local biodiversity and changes to ecosystem processes. Climate change has been predicted to exacerbate the impact of nonindigenous species in the region due to more positive responses to changing environmental conditions compared with native species.

Dana Bergstrom

See also **Auckland Islands; Biogeography; Campbell Islands; Climate Change; Fossils, Plant; Gondwana; Heard Island and McDonald Islands; Kerguelen Islands (Îles Kerguelen); Lichens; Liverworts; Macquarie Island; Mosses; Plate Tectonics; Vegetation**

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FOOD WEB, FRESHWATER

The term food web describes the interrelationships between organisms living in an ecosystem. In lakes, there are two food webs that are linked in terms of the flow of materials like essential nutrients (phosphorus and nitrogen) required for photosynthesis and carbon (a basic biological building block). These are the bottom community, known as the benthos, and the organisms that inhabit the water column, termed the plankton. The ice-free areas of Antarctica, mostly situated on its margins, carry an extraordinary array of lakes that range from freshwater to hypersaline (as much as six times seawater).

Antarctic lakes are usually extremely unproductive due to their low temperatures, low nutrient inputs from the surrounding land, and ice cover, which limit the amount of light energy that can enter the water column to drive the fundamental biological process of photosynthesis. Only the most physiologically robust organisms can survive under these conditions. Microorganisms (bacteria, algae, and single-celled creatures [the Protozoa]) are extremely adept at living in difficult environments and consequently, continental Antarctic lakes are dominated by communities of microorganisms, with few animals and no fish. The food webs are very simple, and there is low species diversity. The radiant energy of the sun is captured by the phytoplankton, which is mainly composed of flagellated protozoa that contain photosynthetic pigments (e.g., cryptophytes, *Pyraminmonas, Chlamydomonas*). In some lakes, photosynthesis is also carried out by ciliated protozoa (e.g., *Mesodinium rubrum, Strombidium*) that contain either symbiotic algae, or plant-pigment-containing organelles called plastids, that they sequester from their algal or flagellate prey and use for photosynthesis. During the process of photosynthesis, the photosynthetic organisms (the phytoplankton) exude some of the material they manufacture into the surrounding water as dissolved organic carbon. This provides a food substrate for the bacteria, which grow, and in turn are fed upon by colourless flagellated and ciliated protozoa. Many of the photosynthetic flagellates also feed on bacteria as a means of augmenting the energy they derive from photosynthesis, especially when the light levels are very low. This is called mixotrophy or mixed nutrition, because it involves a combination of photosynthesis and heterotrophy (animal-like nutrition). In the most southerly, extreme lakes of the McMurdo Dry Valleys, mixotrophic flagellates, particularly cryptophytes, are very common and there is evidence to suggest that during the winter they feed on bacteria and become progressively more dependent on photosynthesis towards summer. Thus one of the keys to survival is nutritional versatility, and mixotrophy is common in protozoan phytoplankton across all Antarctic lakes, but is more predominant in the most extreme systems.

The animals of Antarctic lake plankton are few and extremely adaptable. In the marine derived saline lakes of the Vestfold Hills, for example, the marine microcrustacean (a copepod) *Paralabidocera antarctica* is found feeding on phytoplankton and protozoan plankton. It is the only animal survivor from the seawater that was trapped when the land rose up (isostatic uplift), forming the lakes after the last glaciation. The coastal freshwater and slightly brackish lakes contain a single water flea, *Daphniopsis studeri* (a microcrustacean), that is endemic to Antarctica and its eastern sub-Antarctic islands. These crustaceans appear to remain active all year round, unlike their lower-latitude relatives, which enter resting stages during winter. The Antarctic summer is too short to allow growth from a resting egg to maturity, so these animals have to be ready to reproduce as soon as the summer arrives, enabling their young to grow and build up fat reserves to survive the following winter. Other animals found in the plankton are microscopic rotifers that feed on bacteria, algae, and flagellates. In the extreme Dry Valley lakes, rotifers (species of *Philodina*) are the only animals encountered in the plankton in low numbers. The planktonic animals have no predators, so despite their slow life cycles and low numbers of offspring they can survive in these extremely cold inhospitable waters.

The benthic communities of Antarctic lakes are usually associated with so-called algal mats. These are made up from filamentous Cyanobacteria (blue-green algae), diatoms (algae), and flagellated photosynthetic protozoa. These mats offer a much richer environment than the plankton and provide a habitat for rotifers and many more species of ciliated protozoan, for example, species of *Euplotes, Metopus, Stylonychia,* and microscopic nematode worms. In the coastal freshwater lakes, *Daphniopsis* appears to move between the plankton and the benthic mats to feed. While no crustaceans have ever been recorded in the plankton of the Dry Valley lakes, a copepod was once found in a benthic sample.

Viruses have been described in Antarctic lakes and the marine environment. Viruses are not able to reproduce themselves but must parasitise an animal or plant or a bacterial cell and make that host cell produce more viruses. The virus may continue living in the host cell without causing its destruction, and is passed on during the reproductive cycle of the host to its progeny. Alternatively the virus may cause the destruction of the host cell and the liberation of viruses into the water. Viruses play an important role in aquatic food webs because they parasitise and destroy bacteria and phytoplankton cells. This has the effect of short-circuiting the carbon cycle by destroying these cells before they can be eaten by another organism. Along with bacteria, larger viruses are exploited as food by colourless flagellates. In addition, viruses play a role in transferring genetic material between populations of bacteria in aquatic environments. Viruses are very abundant in Antarctic lakes and their many roles are currently under investigation.

The microorganisms of Antarctica's lakes have attracted considerable attention from the biotechnology industry because they contain bioactive molecules such as low-temperatures enzymes, pharmaceuticals, and antifreeze proteins. A single drop of water is sufficient to set up cultures for such bio-prospecting research, allowing the biological resources of Antarctic lakes to be exploited with virtually no environmental impact.

JOHANNA LAYBOURN-PARRY

See also **Algae; Algal Mats; Benthic Communities in the Southern Ocean; Carbon Cycle; Copepods; Dry Valleys; Dry Valleys, Biology of; Food Web, Marine; Microbiology; Nematodes; Phytoplankton; Protozoa; Rotifers**

FOOD WEB, MARINE

Food webs are topological descriptions of a given community and are typically based on system-specific knowledge of feeding relationships. Only when many interrelated feeding relationships can be quantified to build up detailed food webs can we begin to understand ecosystems. "Who eats whom" appears to be the most central organizing concept in ecology. Therefore, assuming that the emergent behaviour of an ecosystem is, at least partly, dependent on the properties and behaviour of the entities it is composed of, food web characterization is required as an initial step in understanding an ecosystem.

The marine Antarctic ecosystem is taxonomically diverse, structurally complex, and quite variable in time and space. It is composed of interconnected, functionally distinct hydrographic and biogeochemical subsystems, including the open ocean, frontal regions, the shelf-slope waters, the sea ice, and marginal ice zones. The major physical determinant of spatial and temporal changes in the structure and functioning of the marine ecosystem is the annual advance and retreat of the sea ice. The seasonal timing of these events affects life histories of species at every trophic level. However, present knowledge of trophic linkages and energy flow patterns in Antarctic marine communities and ecosystems is still fragmentary. Due to (1) the openness of marine systems and (2) the orders of magnitude in size across the species in marine systems (diatoms vs. whales), the structure of marine food webs is different from that of terrestrial or freshwater ecosystems. Early impressions of the marine Antarctic were seemingly simple food chains leading from phytoplankton to krill *(Euphausia superba)* and further to whales (e.g., minke, *Balaenoptera acutorostrata*). But the system, consisting of many subsystems (e.g., the pelagic microbial loop, nanophytoplankton and picophytoplankton communities, sea-ice communities, and extremely diverse benthic communities on the shelf and slope), is much more complex. Moreover, in the Antarctic, the number of species with extremely numerous feeding links increases the complexity of the Antarctic marine food web. Due to its complexity, the identification of the food web structure or even the construction of a balanced trophic model is a challenging task.

Given the complexity of the system, there is need for a critical evaluation of the tools used to analyze food-web structure. A number of different techniques have been proven useful to provide information on trophic relationships at a variety of organizational scales. These approaches include gut-content analysis, feeding experiments, the use of fatty-acid biomarkers, and stable isotope tracers.

The isotope approach can help to disentangle food web processes at two different scales. Organic substances and living organisms in an ecosystem possess specific levels of stable isotope ratios because a consumer's tissue reflects the composition of its diet. Hence, $\delta^{13}C$ and $\delta^{15}N$ signatures serve as proxies of the trophic distance of an organism from the primary food source of the corresponding food chain. $\delta^{13}C$ signatures are commonly used as carbon source tracers, whereas $\delta^{15}N$ values are a helpful tool for detecting the trophic position and therefore the trophic hierarchy of the system. The stable isotope analysis of the food-web structure of the Antarctic shelf system has revealed that the benthic part of the food web is more complex than the pelagic one.

Pelagic consumers of the Antarctic are mainly dominated by copepods, krill, squids, and pelagic nototheniid fish species (e.g., *Pleuragramma antarcticum*). The benthic part of the food web is more complex, which is due to the high taxon richness and high diversity of feeding types (e.g., some groups, such as the echinoids, feed at more than one trophic level). Benthic fish and invertebrate scavenger–predators, like the nemertean *Parborlasia corrugatus,* are at the top of the food chain. Interestingly, seals, which are supposed to be among the top predators, occupy intermediate trophic levels only. The distance from phytoplankton to pelagic top predators (seals) is about 3.8 trophic levels, whereas the distance to benthic top predators is about 4.6 trophic levels.

Possible explanations for such complexity involve dimensionality of habitats (i.e., three-dimensional habitats, like the Antarctic benthos, may support longer chains than two-dimensional habitats) and species richness (i.e., chains, should be longer in communities supporting larger numbers of species).

Food-web structure and strength of trophic linkages within the functional groups determine the communities' response to and their ability to recover from disturbances. For example, environmental changes apparently affect Antarctic krill, *Euphausia superba,* and its predators. A decline in sea-ice extent at the Antarctic Peninsula has lead to a krill-stock decline and therefore affects associated predators like penguins and whales due to the given mismatch in food supply.

However, trophic decoupling (mismatch in food supply) will have critical consequences in Antarctic marine systems, especially if key species are affected. Therefore, understanding of food-web structure and of ecosystem functioning is necessary for a more efficient approach to resource management and endangered species conservation.

UTE JACOB

See also **Benthic Communities in the Southern Ocean; Biodiversity, Marine; Circumpolar Current, Antarctic; Climate Change; Ecosystem Functioning; Fish: Overview; Food Web, Freshwater; Marine Trophic Level Interactions; Phytoplankton; Sea Ice: Types and Formation; Zooplankton and Krill**

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FOSSILS, INVERTEBRATE

Antarctica has not always been a frozen wasteland. Over geological time the continent, as part of Gondwana, has moved across the globe by plate-tectonic processes, in and out of climatic zones from tropical to polar, and this is reflected in the fossil record, preserved in the sedimentary rocks. In Antarctica, invertebrate fossils are known from the Lower Cambrian onwards and from every geological epoch other than the Silurian, for which no sedimentary rocks have yet been identified (Cooper and Shergold 1991; Crame 1989; Thomson 1991). For the most part they are of marine origin, but there are also rare occurrences of freshwater and terrestrial species. See the table for a simple distribution of invertebrate fossils in Antarctica.

Fauna of Early to Late Cambrian age occur in sedimentary rock sequences scattered through the Transantarctic and Ellsworth mountains. Limestones contain very diverse and varied trilobite faunas, together with conodonts (the jaw apparatus of some tiny marine animal), early molluscs, and brachiopods. The extinct sponge-like archaeocyaths are present in some Early and Middle Cambrian fauna and, more remarkably, in Upper Cambrian limestone of the Ellsworth Mountains (Webers et al. 1992). The Cambrian sequences were deposited in shallow-water environments, and the presence of limestone suggests both warm water and a much lower latitude than the present day. In the main, the trilobite faunas show the closest affinities with those of Australia and the Australo-Sinian Province.

Rocks of Ordovician age are poorly represented but fossils of this age are known from two areas. In the Robertson Bay Group of northern Victoria Land, limestone blocks within a shale–sandstone-conglomerate sequence contain a few trilobites and varied assemblages of conodonts of the earliest Ordovician age. Whereas those fossils have been reworked, trace fossils and body impressions of possible phyllocarid crustaceans in fine- to medium-grained sandstones of the shallow-water Blaiklock Glacier Group, Shackleton Range, represent an *in situ* assemblage (Thomson and Weber 1999).

Through the Transantarctic and Ellsworth mountains is an extensive and thick sequence of mainly sandstone and conglomeratic rocks, known as the Beacon Supergroup. Ranging in age from Devonian to Triassic, it encompasses rocks that record environmental changes from marine (Devonian) to glacial marine and terrestrial (Carboniferous) to ice-free and progressively warmer terrestrial conditions (Permian and Triassic). Devonian marine faunas occurring in the Ellsworth Mountains and Horlick Range include

Simplified Distribution of Antarctic Invertebrate Fossils Through Time and by Location

Time*	Period†		Principal Fossils	Key Locations
2	Quaternary		Bryozoans, Molluscs	South Shetland Islands, McMurdo Sound
24	Tertiary	L	Bryozoans, Molluscs, Crustaceans	Cockburn Island, South Shetland Islands, Marine Plain
65		E	Corals, Brachiopods, Molluscs, Crustaceans, Serpulids	Seymour Island
99	Cretaceous	L	Brachiopods, Molluscs, Echinoderms, Crustaceans	James Ross Island
144		E	Brachiopods, Molluscs, Echinoderms, Crustaceans	Alexander Island, James Ross Island, South Shetland Islands
159	Jurassic	L	Brachiopods, Molluscs, Echinoderms, Crustaceans	Alexander Island, NE Antarctic Peninsula, East Palmer Land, East Ellsworth Land
180		M	Molluscs	East Ellsworth Land, South Shetland Islands
206		E	Molluscs Freshwater molluscs, Beetles	Alexander Island N Antarctic Peninsula
227	Triassic	L	Bivalves	NW Antarctic Peninsula
242		M	Radiolarians	South Orkney Islands
248		E		
256	Permian	L		
290		E	Freshwater bivalves & crustaceans, Insects	Horlick Mountains, Ellsworth Mountains
323	Carboniferous	L	Bryozoans, Brachiopods	Alexander Island
354		E	Molluscs, Crinoids	
370	Devonian	L		
391		M		
417		E	Brachiopods, Molluscs	Horlick Mountains, Ellsworth Mountains
423	Silurian	L	No sedimentary rocks of this age known in Antarctica	
443		E		
458	Ordovician	L		
470		M	Crustaceans	Shackleton Range
490		E	Trilobites, Conodonts	Northern Victoria Land
500	Cambrian	D		Ellsworth Mountains
512		C	Archaeocyaths, Trilobites, Molluscs	Transantarctic Mountains
520		B		
543		A		

Geologic timescale is after Palmer and Geissman (1999).
*Age in millions of years of the boundary picks for the base of the subdivision.
†Shaded subdivisions indicate generalised occurrences of fossils of early (E), middle (M), or late (L) age and do not imply that a complete succession is present.

brachiopods, bryozoans, molluscs, and trilobites, which show faunal affinities with those of the Falkland Islands and South Africa. No invertebrate fossils are known from the Carboniferous of the Transantarctic Mountains, where the rocks record an extensive glaciation that covered not only Antarctica, but also large areas of South America, southern Africa, India, and Australia. Whereas the Permian rocks are more famous for their flora, there are isolated records of insects and, more commonly, conchostracans (bivalved ‘‘shrimp’’) and even freshwater bivalves. The Triassic sequences of the Transantarctic Mountains are of terrestrial origin and notable for their vertebrate fauna; no records of any invertebrate fossils have yet been published from them.

By contrast, the Mount King Formation of eastern Alexander Island contains limited but varied fauna of the mid-Carboniferous to possible earliest Permian age. These include bryozoans, brachiopods, crinoids, and a variety of molluscs (Kelley et al. 2001). It is possible that the enclosing rocks are exotic and became attached to Antarctica by the process of accretion at the proto-Pacific margin; faunal affinities are with Argentina and eastern Australia. Likewise, we have to look to the Antarctic Peninsula for the only evidence of Triassic invertebrate fauna in

Antarctica. Chert from within the Greywacke Shale Formation of the South Orkney Islands contains Triassic radiolarians and the Legoupil Formation of the northwestern Antarctic Peninsula, a bivalve fauna of New Zealand and Japanese affinity.

Jurassic strata are widespread in the Antarctic Peninsula. Early and Middle Jurassic sequences are patchy, but those of the Late Jurassic are more complete. All marine fauna are dominated by molluscs, notably ammonites. Localised Early Jurassic fauna in Alexander Island come from an accretionary complex and could be exotic; all other fauna are *in situ*. Freshwater plant-bearing shales at the northern Antarctic Peninsula contain bivalves and rare beetle remains. Middle Jurassic fauna occur in the South Shetland Islands and eastern Ellsworth Land, and Late Jurassic fauna are both varied (dominated by ammonites, belemnites, and bivalves, but also with brachiopods, echinoderms, and crustaceans) and widespread; faunal affinities are generally with those of Patagonia, New Zealand, Indonesia, and the Himalayan region.

The macrofauna of the Cretaceous are also mollusc dominated and show a mixture of regional and more cosmopolitan affinities. Fossils are locally numerous and varied, including corals, bryozoans, brachiopods, molluscs, echinoderms, crustaceans, and serpulid worms. By piecing together the fossil records from Alexander Island, South Shetland Islands, and James Ross Island area, an almost "complete" Cretaceous faunal succession has emerged. Preservation of many Late Cretaceous species is excellent (e.g., ammonites [Macellari 1986] and crustaceans [Feldmann et al. 1993]). Foraminifera (microfossils) are preserved for the first time in the Antarctic fossil record in both Cretaceous and Tertiary rocks.

Outcrops of Cenozoic (Tertiary) marine sedimentary rocks are of very restricted occurrence, being limited mainly to King George and Seymour Islands in the northern Antarctic Peninsula region, but this is outweighed by the variety and quality of preservation of the fossils (Gazdzicki 1987; Stillwell and Zinsmeister 1992). Ammonites were extinct but the dominant forms are still molluscs, with gastropods appearing in large numbers for the first time. The fauna as a whole are even more varied, with corals, bryozoans, brachiopods, echinoderms, and crustaceans, locally in abundance. Although there are some similarities with fauna from New Zealand and South America, the fauna generally reflect the isolation of Antarctica. Fossiliferous erratics in McMurdo Sound indicate that Tertiary sequences may be present there somewhere beneath the ice.

Quaternary fossils, mainly bivalves, are even more scattered but may be found almost anywhere around Antarctica where there are raised beach deposits. However, a remarkable find of molluscs, bryozoans, and serpulid worms in a borehole off Cape Roberts (Taviani et al. 1998) suggests that more discoveries await. But perhaps the most exciting discovery would be that of fossiliferous Silurian sedimentary rocks and, even more, that of graptolites, a group unknown from Antarctica.

Michael R. A. Thomson

See also **Antarctic Peninsula; Beacon Supergroup; Fossils, Plant; Fossils, Vertebrate; Gondwana; Plate Tectonics; South Orkney Islands; South Shetland Islands; Transantarctic Mountains, Geology of; Victoria Land, Geology of**

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FOSSILS, PLANT

Although Antarctica is now a land of snow and ice, for most of its past it was covered in lush vegetation. Forests thrived on the continent, even though it was situated over the South Pole. The fossilised remains of this vegetation are now preserved as permineralised logs and tree stumps, as impressions of leaves and flowers, and as microscopic pollen preserved in the rock strata. Using these plant fossils, it is possible to reconstruct the composition of these ancient forests and decipher the climate signal stored in them to understand how Antarctica's climate has changed over millions of years.

The oldest fossil plants in Antarctica are of Permian age (~250 million years old) from a sequence of rocks called the Beacon Supergroup in the Transantarctic Mountains. The strata are composed of sandstones (formerly sand that was once deposited in river beds), and coal seams that originated as peat swamps. Fossil tree stumps can be found in their original growth positions within coal seams, along with tree trunks and leaf imprints. Large oval fossil leaves called *Glossopteris* are very common, representing a type of tree that is now extinct. *Glossopteris* leaves are famous Antarctic fossils, since Scott and his party collected samples from the Beardmore Glacier region during their ill-fated trip to the South Pole. The leaves are also found in South America, southern Africa, and Australia, and are important evidence that these lands were once joined together as the great southern continent of Gondwana.

Evidence from the rocks indicates that *Glossopteris* trees were well adapted to living in cool wet climates that prevailed in Antarctica in the Late Permian, after the melting of the great Gondwanan ice sheets. However, by the end of the Permian (~245 Ma), Antarctic climates had warmed up and *Glossopteris* become extinct, and in the following Triassic period the vegetation was dominated by plants with thick waxy leaves that could tolerate dry conditions. The fern *Dicroidium* was especially common in Antarctica at this time.

Forests continued to cover Antarctica in the Jurassic, but as Gondwana broke up about 180 Ma, volcanic eruptions spewed lava over the land surface, trapping the trees in floods of lava. The vegetation survived, and until about 100 Ma, a simple flora of conifer trees, ferns, and the cycad-like fossils, called bennetites, thrived in a warm climate. One of the first significant fossil plant localities discovered in Antarctica is the Early-Middle Jurassic Mount Flora fossil assemblage, near Hope Bay at the tip of the Antarctic Peninsula. It was discovered by geologist Johann Gunnar Andersson during the Swedish South Polar Expedition (1901–1904) and remains of exceptional scientific importance today.

Some of the most spectacular fossil forests in Antarctica are preserved within mid-Cretaceous (100-million-year-old) rocks on Alexander Island, on the west side of the Antarctic Peninsula. Hundreds of fossil trees and shrubs are preserved in their positions of growth, buried within sandstones that were deposited during catastrophic floods from volcanic uplands. Studies of the spacing of the stumps and plant types illustrate that these forests were as dense as any normal temperate forests that grow in low latitudes today, even though the Alexander Island forests grew in latitudes as high as 70° S. At this latitude it is thought that the plants tolerated the extreme polar light regime by becoming dormant in the long dark winters and flourishing during the summer days of midnight sun.

The first appearance of fossils of flowering plants (angiosperms) during the Late Cretaceous marked a change in Antarctic vegetation. Fossil floras from the South Shetland Islands and the eastern side of the Antarctic Peninsula (from James Ross Island and Seymour Island in particular) are dominated by leaves of flowering trees. Many fossil leaves are similar to those of families that live in subtropical climates today, indicating that warm, wet climates extended southward to cover Antarctica in much warmer global climates. Quantitative analysis of physical features of the leaves can be used to estimate the climate in which the trees grew, for the Late Cretaceous mean annual temperatures of about 19°C prevailed, with warm, frost-free winters.

Subtropical floras grew in warm climates on the volcanic arc of the Antarctic Peninsula for millions of years, surviving the environmental catastrophe that saw the extinction of the dinosaurs 65 Ma at the end of the Cretaceous period. A younger flora, about 60 million years old, from the Palaeocene epoch, was discovered on Seymour Island by Otto Nordenskjöld while his party was abandoned due to shipwrecks during the Swedish South Polar Expedition (1901–1904). The leaves were first described by Dusén in 1908, and recognised as ancestors of the temperate vegetation living today in South America and Australia.

Fossil plants of Eocene age (~55–40 Ma) hold vital clues to a major change in climate at that time. The warm-loving types disappeared, replaced instead by trees that were tolerant of cool climates. In particular, the southern beech *Nothofagus* became most common in Antarctic forests, along with the "monkey puzzle" conifer *Araucaria*. Leaf analysis suggests that by 40 Ma, mean annual temperatures had dropped to around 10°C, with winter temperatures below freezing.

Geological evidence from other regions of Antarctica suggests that ice sheets were well developed on the continent by this time, marking a major change from greenhouse to icehouse climates.

The onset of glaciation and cold climates led to the demise of Antarctic vegetation. Plant macrofossils are rare from rocks younger than 40 million years old, but fossil pollen shows that tundra vegetation was present, with small bushes of *Nothofagus,* mosses, and rare conifers. In the Beardmore Glacier region of the Transantarctic Mountains, a unique flora of dwarf *Nothofagus* bushes, cushion plants, and mosses is preserved sandwiched between glacial deposits. Preserved in their growth positions, these plants grew only 300 miles from the South Pole and indicate a short burst of climatic warmth and glacial retreat during the icehouse world. These fossils heralded the end of Antarctica's ancient forests as the glacial landscape took over. Will forests return in the future as our climate warms?

JANE FRANCIS and VANESSA THORN

See also **Antarctic Peninsula, Geology of; Beacon Supergroup; Biodiversity, Terrestrial; Climate Change; Coal, Oil, and Gas; Ferrar Supergroup; Fossils, Invertebrate; Fossils, Vertebrate; Nordenskjöld, Otto; Swedish South Polar Expedition (1901–1904); Transantarctic Mountains, Geology of**

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FOSSILS, VERTEBRATE

Since the discovery of the first Triassic terrestrial vertebrate fossil from Antarctica in 1967, three significant Mesozoic faunas have been identified and described from the southern Transantarctic Mountains in areas approximately 500–600 miles from the Geographic South Pole. Early Triassic (245 Ma) vertebrates occur at numerous localities in exposures near the Beardmore and Shackleton Glaciers. An early Middle Triassic (225 Ma) assemblage has been described from two localities in the Gordon Valley discovered in 1985–1986 and more recently (2003) from Fremouw Peak; both of these sites are in the Beardmore Glacier region. Finally, an Early Jurassic dinosaur fauna was found in 1990–1991 on Mt. Kirkpatrick near the Beardmore Glacier.

The Early Triassic fossil vertebrates occur at numerous levels in fine- to medium-grained fluvial sediments of the lower Fremouw Formation. The fauna of the lower Fremouw have been the most extensively collected and studied of the three fauna from the southern Transantarctic Mountains. This fauna includes a diverse assemblage, consisting of the therapsid reptiles *Lystrosaurus murrayi, Lystrosaurus curvatus, Lystrosaurus mcCaigi, Myosaurus gracilis, Thrinaxodon liorhinus, Eriolacerta parva, Peadeosaurus parvus, and Rhigosaurus glacials*. *Lystrosaurus* is a very common Early Triassic dicynodont known from a number of other Gondwana continents in addition to Antarctica. *Myosaurus* is a very small, rare dicynodont known only from South Africa and Antarctica. The dicynodonts are a common group of herbivores in the Late Permian and Triassic periods worldwide. *Thrinaxodon* is a weasel-sized carnivorous cynodont that also occurs in South Africa. *Eriolacerta, Peadeosaurus,* and *Rhigosaurus* are all small scaloposaurids, a group that is typical of the Late Permian in South Africa.

Occurring with the therapsids in lower Fremouw Formation are the prolacertid *Prolacerta broomi,* the procolophonid *Procolophon trigoniceps,* the temnospondyls *Austrobrachyops jenseni* and *Cryobatrachus kitchingi,* and an indeterminate rhytidosteid. Prolacertids are a primitive group related to modern lizards, and procolophonids were small and lizard-like but not closely related to lizards. The temnospondyls were a fairly diverse group of extinct semiaquatic amphibians during the Permian and Triassic ranging in length from less than a meter to the size of a large crocodilian. All three of the Early Triassic temnospondyls from Antarctica are relatively small.

The Middle Triassic fauna from the upper Fremouw Formation of Antarctica again include therapsids and temnospondyls; however, they are generally much larger than most of the Early Triassic forms. A large kannemeyerid dicynodont occurs along with the large cynodont *Cynognathus,* a more derived indeterminate cynodont, and a gomphodont that shares some features with the Middle Triassic traversodontids. Gomphodonts were medium-sized herbivores related to the cynodonts. The temnospondyls from the upper part of the Fremouw Formation include two very large capitosaurs, with skull lengths of nearly 1 m.

The youngest vertebrate fauna from the southern Transantarctic Mountains were collected from the Hanson Formation on Mt. Kirkpatrick near the Beardmore Glacier at an elevation of about 4000 m. This Early Jurassic assemblage includes the partial skeleton of *Cryolophosaurus ellioti,* a 7-m-long carnivorous theropod dinosaur unique to Antarctica. The name means "frozen crested reptile" in reference to its polar occurrence and the unusual bony display crest on top of the skull. Teeth of small scavenging theropods, partial remains of a plateosaurid prosauropod, a tooth from a tritylodont, and the humerus of a pterosaur were also recovered from the same locality. A new locality in the same formation was discovered in 2003 on Mt. Kirkpatrick. To date, this new site has yielded remains of a true sauropod, with much of the material still under study. Sauropods are the large, long-necked, long-tailed herbivores such as *Apatosaurus* and *Brachiosaurus* known from the Jurassic on other continents. Prosauropods were a group of generally small animals that resembled the true sauropods and may be related to them. The tritylodonts represent the last of the therapsids and were rather beaver-like in appearance and habits. Pterosaurs are the flying reptiles that coexisted with the dinosaurs during the Mesozoic.

In addition to the vertebrate fauna from the southern Transantarctic Mountains, several other fauna are known from other regions of Antarctica. In 1999 a short reconnaissance expedition to Southern Victoria Land in the northern part of the same range near McMurdo Station led to the discovery of a few bone fragments from the Upper Triassic Lashly Formation. Consequently, there are now terrestrial vertebrates of four different ages from the Transantarctic Mountains. However, exposures of Upper Triassic rocks in Southern Victoria Land are not extensive and the fossils are extremely fragmentary. Only a single dicynodont tusk and some indeterminate small limb pieces were recovered.

On the other side of the continent, Late Cretaceous (70 million years old) vertebrates have been found on several islands near the Antarctic Peninsula. Skeletons of plesiosaurs and mosasaurs occur in shallow marine deposits on these islands. Plesiosaurs are extinct marine reptiles with long serpentine necks that coexisted with the dinosaurs in the Mesozoic. Mosasaurs are extinct marine reptiles that are closely related to modern lizards. Both plesiosaurs and mosasaurs were carnivorous.

In addition to the marine animals, the Cretaceous deposits have produced a few fragmentary dinosaurs. These include a nodosaurid, a small hypsilophodontid, a single tooth from a hadrosaur, and a small theropod. The nodosaurs are a group of armoured herbivores related to the ankylosaurs. Hypsilophodontids are small herbivorous ornithopod dinosaurs and hadrosaurs are the larger herbivorous "duck-billed" dinosaurs.

The only non-Mesozoic Antarctic fossil vertebrates were also collected from the Antarctic Peninsula region. These specimens include only a few fragmentary jaw specimens of a small Eocene-age marsupial mammal. This find supports the theory that marsupials originally migrated from South America across Antarctica to reach Australia.

Other than the terrestrial fauna described already, the only additional Antarctic vertebrate fossils come from two bony fish fauna from Devonian deposits in the Horlick Mountains near the southern portion of the Transantarctic Mountains and from Middle Jurassic lake interbeds near the Beardmore Glacier.

Since 98% of Antarctica is covered with glacial ice, the potential for future fossil vertebrate discoveries is limited. By far the most likely place new finds will be made is in the extensive early- to middle-Mesozoic deposits of the Southern Transantarctic Mountains.

William R. Hammer

See also **Antarctic Peninsula, Geology of; Gondwana; Transantarctic Mountains, Geology of; Victoria Land, Geology of**

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FOYN, SVEND

Svend Foyn (July 9, 1809–November 11, 1894) was a Norwegian sealing and whaling entrepreneur whose method of whaling became the model for the industry as it developed in the Northern Hemisphere and later in Antarctic waters.

Foyn was born in the town of Tønsberg, a busy shipping port. He went to sea as a boy on family-owned vessels. He was a captain at 24, and worked in the timber trade—a favoured trade in Norway in the heyday of the sailing-ship era. However, in 1844 his career took a new turn, when he went on a sealing voyage to the Arctic. After returning home, he built his first sealer—a sailing vessel with an auxiliary steam engine. It became a model of design. Foyn built more vessels, and so did other merchants. Arctic sealing became a new maritime growth industry in the region.

Foyn's entrepreneurial skills led him into yet another industry. He felt that the competition in sealing, due to its large expansion, had become too intense. In his years in northern Norway and the Arctic, he had observed the abundance of rorquals—blue whales, fin whales, and humpback whales. At that stage in the history of whaling they had not been heavily exploited. While sperm whales and right whales could be caught by traditional methods, employing rowboats, and hand-held harpoons and lances, the powerful, fast-swimming rorquals were beyond reach of these tools. New methods had to be developed to chase them successfully. Foyn put his inventive energy into this work, and in the early 1860s he put into practice a method of whaling that dramatically altered the further development of the entire industry. The two most important components of this new concept were the harpoon cannon and the steam catcher boat. Several other Norwegian and American inventors had worked on the development of whale cannon, but Foyn brought the ideas together in a practical solution in his cannon with an explosive grenade harpoon. The whaling vessel of his design, *Spes & Fides*—94 feet (29 m), and schooner-rigged with a steam engine—was built in 1863. It was large and powerful enough to handle the strong, fast rorquals. A third important element in his whaling enterprise was a land-based processing plant, a shore station. He built one in Vadsø, Finnmark, in 1870.

Foyn was able to protect his entire system of whaling by patents, so for all intents and purposes, he had a monopoly until 1881. At that point, businessmen in Tønsberg and the neighbour town Sandefjord were anxious to enter the business. A new industry was created and expanded throughout the 1880s and 1890s.

In the early 1890s, the whaling community in Norway and elsewhere started to consider the Antarctic as having potential whaling grounds. Foyn was about to retire, but, when approached by his younger relative Henrik J. Bull, he paid for an expedition in search of whales. Foyn bought a former sealing vessel that was refitted and named *Antarctic*. The expedition was away from 1893 to 1895. Foyn died while it was down south, and thus was not able to see its results, nor the next phase of the development of the whaling industry: Antarctic whaling.

The entirety of Svend Foyn's own career was associated with the Northern Hemisphere. Nevertheless, he played a major role in the development of Antarctic whaling. First, the whaling concept he developed—shore stations with small, powerful, cannon-equipped steamers—was adopted at South Georgia and elsewhere beginning in 1904. Many of those Norwegian Antarctic whaling pioneers had their first experience at Finnmark. Second, the expedition Foyn funded, which included Carsten Borchgrevink, was not only a significant adventure of the early Heroic Age of Antarctic exploration, but also was the necessary background to the growth of the Antarctic whaling industry. The ship in that expedition—*Antarctic*—even made a second famous journey, carrying Otto Nordenskjöld's Swedish expedition of 1901.

For all his life, Foyn was a very religious man. He was married twice, but left no children. His large fortune was given to missionary concerns.

Bjørn L. Basberg

See also **Borchgrevink, Carsten E.; Norwegian (Tønsberg) Whaling Expedition (1893–1895); Swedish South Polar Expedition (1901–1904); Whaling, History of**

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FRANCE: ANTARCTIC PROGRAM

The Institut Polaire Français Paul-Emile Victor (IPEV) is commissioned by the French government to organize the research activities in the Antarctic and sub-Antarctic French Territories, where extreme climatic environmental conditions require specific technologies. IPEV was created in January 2002 as a successor to the Institut Français pour la Recherche et la Technologie Polaires (IFRTP), created 10 years before to take over the scientific research activities conducted by the Expéditions Polaires Françaises (EPF) since 1947 in the Antarctic (Terre Adélie), and by the Mission de Recherche du Territoire des Terres Australes et Antarctiques Françaises (TAAF) since 1956 in the sub-Antarctic French Territories (South Indian Ocean islands: Kerguelen, Crozet, Saint-Paul, Amsterdam).

In its capacity of funding agency, IPEV coordinates, supports, and implements national and international scientific and technological research programs in the Antarctic and sub-Antarctic regions; selects and supports specific scientific and technological operations in the Antarctic; organizes and promotes scientific expeditions; and contributes to international scientific and technological planning by maintaining regular and close communications with similar foreign polar organizations.

IPEV also organizes research cruises on board *Astrolabe* and *Marion Dufresne,* the Antarctic and sub-Antarctic French Islands supply vessels, and contributes to the development of large European oceanographic programs.

The research programs supported by IPEV are relevant to Earth and planetary sciences, atmospheric sciences, glaciology, oceanography, marine and terrestrial life sciences, and human biology and medicine, and include many multidisciplinary approaches. In addition to the permanent observatory activities and the basic field operations involving many disciplines—like geology, seismology, geomagnetism, geodesy, glaciology, oceanography, meteorology, aeronomy, astronomy, astrophysics, biology, and medicine, run by major French universities (Aix-Marseille II et III, Besançon, Bordeaux 1, Boulogne-sur-Mer, Grenoble 1, Lyon I, Montpellier II, Nice-Sophia, Orléans, Paris VI, Rennes I, Saint-Etienne, Strasbourg 1, Versailles) and large research organizations (CEA, CNRS, ENSG, EOST Strasbourg, EPHE, IREMER, IPG Paris, MNHN)—IPEV contributes to the promotion of the International Polar Year program (IPY +50) and adheres to the five new international programs recently identified by SCAR: "Antarctic Climate Evolution" (ACE), "Antarctica and the Global Climate System" (AGCS), "Evolution and Biodiversity in the Antactic" (EBA), "Interhemispheric Conjugacy Effects in Solar-Terrestrial and Aeronomy Research" (ICESTAR), and "Subglacial Antarctic Lake Environments" (SALE).

IPEV corresponds to a "Groupement d'Intérêt Public" in which the Ministry of National Education and Research and the Centre National de la Recherche Scientifique (CNRS) are the leading partners. Other government bodies and public or private organizations like the Foreign Office, the Terres Australes et Antarctiques Françaises (TAAF), the Commissariat à l'Energie Atomique (CEA), the Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER), the Centre National d'Etudes Spatiales (CNES), the Méteo-France and the Expéditions Polaires Françaises (EPF), are also associated with IPEV but at a lower level.

As the national polar funding agency, IPEV directly supports the activities of the Comité National Français des Recherches Arctiques et Antarctiques (CNFRA), founded at the time of the International Geophysical Year (1957–1958) by the French Academy to promote polar research programs. The main purpose of CNFRA is to provide a forum for French scientists involved in Antarctic research to discuss their field operations and plans and to promote collaboration between them. CNFRA is also the official French representative on the Scientific Committee on Antarctic Research (SCAR), an international body established in 1958 by the International Council of Scientific Unions (ICSU), in charge of the coordination of scientific activity in the Antarctic.

All the partners of the French Polar Institute (IFRTP-IPEV) listed above are members of the board of directors, chaired between 1992 and 1998 by Claude Lorius (IFRTP) and now by Jean Jouzel (IPEV). A Science Council with disciplinary representation, acting as an advisory and expert group, was established in 1992 and successively chaired by Roland Schlich (1992–1997) and Yvon Le Maho (1998–2001). In 2002 this council was replaced by a "Science and Technology Program Council" chaired by Edouard Bard.

The director of the French Polar Institute is elected by the board of directors. Between 1992 and 1997 IFRTP was headed by Roger Gendrin (CNRS) and now IPEV is headed by Gérard Jugie (CNRS).

The annual budget of the French Polar Institute is about 30 million with a permanent staff of about 50 engineers and technicians (not including the additional staff recruited on a time basis to staff the annual expeditions and summer season campaigns). Most of the funds are provided by the Ministry of Research and the Centre National de la Recherche Scientifique (CNRS); these resources are mainly devoted (90%) to run the Antarctic and sub-Antarctic science activities and the corresponding logistics.

Roland Schlich

See also **Amsterdam Island (Île Amsterdam); Antarctic Treaty System; Crozet Islands (Îles Crozet); France: Institut Polaire Français Paul-Emile Victor (IPEV) and Terres Australes et Antartiques Françaises (TAAF); International Geophysical Year; Kerguelen Islands (Îles Kerguelen); St. Paul Island (Île St. Paul); Scientific Committee on Antarctic Research (SCAR)**

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IPEV website. http://www.ipev.fr
SCAR website. http://www.scar.org

FRANCE: INSTITUT POLAIRE FRANÇAIS PAUL-EMILE VICTOR (IPEV) AND TERRES AUSTRALES ET ANTARTIQUES FRANÇAISES (TAAF)

Two French organizations are in charge of the Southern French Territories, the sub-Antarctic Îles Kerguelen, Îles Crozet, Île Amsterdam, and Île St. Paul, and Terre Adélie, in Antarctica:

Terres Australes et Antarctiques Françaises (TAAF) is the official representative of the French government. The organization is responsible for national sovereignty and has powers to enforce law and order. It issues permits required by the Protocol on Environmental Protection to the Antarctic Treaty and authorizations to access protected areas. The budget of 26 million per year is provided by the Ministry of Overseas Territories and by external resources (fisheries, tourism, tax for ship registration, philately).

The French Polar Institute *Paul-Emile Victor* (IPEV) is a support agency for research in polar and subpolar regions. Originally created in 1992, IPEV has the status of Public Interest Group (Groupement d'Intérêt Public, GIP). The partners of this GIP are the following: French Ministry for Research, French Ministry of Foreign Affairs, National Centre for Scientific Research (CNRS), French Atomic Energy Commission (CEA), French Research Institute for Exploitation of the Sea (Ifremer), French Meteorological Agency (Météo-France), French Space Agency (CNES), French Austral and Antarctic Territories (TAAF), and French Polar Expeditions. The missions of IPEV are to provide the legal framework and the human, logistic, technical, and financial means for the development of French research in the Arctic, sub-Antarctic, and Antarctic. In this context, IPEV (1) supports and implements national and international scientific programs; (2) organises scientific expeditions; and (3) builds and maintains infrastructure and equipment in support of research. IPEV also organises marine science expeditions on board the vessels it operates.

The resources allocated to scientific, technical, and logistic activities in the field represent more than 90% of IPEV's annual budget. These include capital expenditure for scientific equipment, infrastructure, and vehicles as well as operating costs such as the charter and operation of vessels and salaries and travel expenses to and from the polar regions for field personnel.

Some sixty research programs covering all disciplines are selected every year by IPEV on the recommendation of its council on polar scientific and technological programs. A large proportion of these programs are based on field activities in the southern polar regions: Terre Adélie and Dôme C in the Antarctic, and Îles Kerguelen, Îles Crozet, and Île Amsterdam in the sub-Antarctic. In the Arctic, programs are carried out in summer in Svalbard using the research support infrastructure managed by IPEV at the international scientific station of Ny-Alesund. A Memory of Understanding was recently signed with the Alfred Wegener Institute (AWI) in order to gather the logistics facilities of the two organizations at Ny-Alesund.

In the Southern Indian Ocean, TAAF operates three sub-Antarctic research stations at Îles Kerguelen, Îles Crozet, and Île Amsterdam. They are serviced by *Marion Dufresne,* a multipurpose vessel chartered for resupply operations. Every year, four voyages of *Marion Dufresne* out of La Réunion Island in the Indian Ocean carry personnel and supplies to the stations.

The research station in Îles Crozet has operated since 1964. The station accommodates around twenty staff over winter. The research station in Îles Kerguelen was first established in 1951, and saw a significant development during the International Geophysical Year (1957–1958). The station accommodates about sixty staff over winter. The research station in Île Amsterdam has operated since 1950, and accommodates about twenty staff over winter.

In Terre Adélie, IPEV operates the Dumont d'Urville Station, located in a rocky archipelago on the edge of the Antarctic continent, which is only accessible by sea during summer in the southern hemisphere, the austral summer, from mid-December to mid-March. The supply vessel, *L' Astrolabe,* makes five return voyages between Hobart in Tasmania and Dumont d'Urville over the summer. IPEV manages the entire operation of the station and the support to its research programs. The station accommodates around thirty staff in winter and about one hundred staff in summer.

IPEV operates also with its Italian partner (PNRA) the new French–Italian research station Concordia, at Dôme C, at about 3200 m altitude and at 1100 km from DDU and 1200 km from Mario Zuchelli Station, at Terra Nova Bay (Italian research station). Concordia can accommodate sixteen persons over winter, researchers, technicians, a doctor, and a chef, living a totally self-sufficient life for 9 months. The first wintering-over started in February 2005 with thirteen staff.

Surface convoys composed of heavy tractors, trailers, and sleds and known as "traverses" operate between Dumont d'Urville and Dôme C to deliver all equipment for the construction and operation of Concordia station and the conduct of its research programs. Three traverses are usually organized each year. An annex station, Cape Prud'homme, located on the Antarctic continent off Dumont d'Urville, supports the organisation of the surface convoys.

IPEV and TAAF assist the French Ministry of Foreign Affairs in the Antarctic Treaty System. IPEV chairs the Council of Managers of National Antarctic Programs (COMNAP) during the 2005–2007 period and the European Polar Board as well. It participates also in the Europolar Consortium, gathering twenty-five Ministries, Funding Agencies, and National Polar RTD Authorities from nineteen European countries in order to pave the way for a "European Polar Entity."

Yves Frenot

See also **Amsterdam Island (Île Amsterdam); Antarctic: Definitions and Boundaries; Antarctic Treaty System; Council of Managers of National Antarctic Programs (COMNAP); Crozet Islands (Îles Crozet); France: Antarctic Program; French Naval (*Astrolabe* and *Zélée*) Expedition (1837–1840); International Geophysical Year; Kerguelen Islands (Îles Kerguelen); Protocol on Environmental Protection to the Antarctic Treaty; St. Paul Island (Île St. Paul)**

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FRENCH ANTARCTIC *(FRANÇAIS)* EXPEDITION (1903–1905)

Jean-Baptiste Charcot's 1903–1905 expedition in *Français* is one of the least-known expeditions of the Heroic Age of Antarctic exploration. Charcot's father had died in 1893, leaving an inheritance that enabled Charcot's long-maturing ideas for travel and exploration to be achievable. He commissioned the construction of *Français,* to be rigged as a three-masted schooner, from the well-known firm of Gauthier in Le Havre. The specification provided for the best materials to be used, and Charcot took advice from Adrien de Gerlache with regard to the equipping of the ship. His original intention was to travel north but, on news reaching Europe that Otto Nordenskjöld in *Antarctic* was overdue and presumably in difficulties, he redirected his attention southwards.

Charcot was fortunate in being able to secure additional support from Paul Pléneau, a wealthy engineer, and from various official French bodies and the newspaper *Le Matin,* the proprietor of which was his brother-in-law. The expedition also had the support of the French government. In addition to providing aid for the Nordenskjöld search effort, Charcot's plans included the exploration of the west coast of the Antarctic Peninsula as far south as Adelaide and Alexander Islands, discovered by John Biscoe and Fabian von Bellingshausen, respectively. A full research programme was to be undertaken and several officers with scientific interests were on board.

A tragic accident delayed departure, but *Français* finally left Le Havre on August 27, 1903, with Pléneau and de Gerlache as members of the expedition.

However, on arrival in Brazil, and to Charcot's disappointment, de Gerlache left the expedition. Upon reaching Buenos Aires, news was received of the rescue of Nordenskjöld and his men, enabling Charcot to proceed with an exploratory expedition, unhampered by humanitarian considerations. *Français* left Buenos Aires on December 23, and ventured into the Drake Passage from Tierra del Fuego on January 27, 1904. After a rapid voyage, she arrived in the South Shetland Islands on February 1, and proceeded southwest, passing along the coasts of the Palmer Archipelago. On February 5, the boiler pipes ruptured and serious engine problems were experienced but, despite this difficulty, Charcot pressed on to Flanders Bay where repairs were made. However, constant problems with the engines—which had been purchased secondhand due to decreasing funds—were experienced throughout the rest of the voyage.

On February 19, *Français* reached Wiencke Island and an inlet that Charcot named Port Lockroy after Edouard Lockroy, the Vice-President of the Chamber of Deputies and a great supporter of the expedition. Continuing southwards, and despite further engine problems, *Français* passed latitude 65° S, where he searched for a suitable wintering site. He determined that an inlet on Booth Island was adequate for the purpose.

Nowhere is Charcot's natural skill as an explorer revealed more clearly than in the methods he adopted with regard to this wintering. The *Français* expedition was one of the best equipped of all the expeditions of the first 2 decades of the twentieth century, and Charcot had taken careful notice of the problems experienced by de Gerlache during the *Belgica* expedition. *Français* carried material for the construction of buildings for the accommodation of scientific instruments, and the most careful preparations had been made for the welfare of the crew. These included the provision for each man of as much privacy as possible and of varied, and good, food and drink. Lectures were given and discussion groups were held to combat boredom. Whenever conditions permitted, groups went ashore for scientific and recreational purposes.

In spring, on November 24, a whaleboat expedition set forth with the aim of reaching Petermann Island and surveying a large portion of the Graham Land coast. Despite very considerable difficulties arising from the presence of large ice masses in the narrow channels of the area, and from snow blindness, the trip was a success, and much accurate mapping was achieved.

With the approach of summer, and the clearing of ice from the bay by the winds, *Français* was able to set sail and continued southwards, rounding the Biscoe Islands and passing inland of Adelaide Island. On January 13, 1905, Alexander Island was sighted, but shortly thereafter *Français* struck a submerged rock. The ship was badly holed and made water fast, necessitating the use of the crew to power the pumps, the engines still being inefficient. In addition, the weather was deteriorating, so Charcot had no option but to head northwards in an attempt to reach appropriate shelter in which repairs could be effected. Eventually *Français* reached Wiencke Island after a voyage of 16 days—during which the pumps were continually manned. Repairs took 10 days, after which Charcot continued north, arriving at Smith Island on February 15, and eventually Puerto Madryn and Buenos Aires.

In Buenos Aires the ship was examined in dry dock and the extent of the damage, which was considerable, was fully revealed. She was sold to the government of Argentina, and the members of the expedition returned to France aboard a passenger vessel, taking with them some seventy-five boxes of scientific specimens, records, and charts.

Despite the continual problems that were experienced with the engines, and the accident, the results of the *Français* expedition were most impressive. More than 600 miles of difficult coast had been charted, and the scientific results were the most detailed to have yet been secured from the area of the Antarctic Peninsula. The expedition also established Charcot's high rank as an explorer. In addition to his extremely good planning, he had demonstrated excellent leadership in serious difficulties. He had succeeded in the most difficult task of maintaining morale throughout the expedition. An appreciative French government paid for the publication of the scientific results, which totaled eighteen volumes.

IAN R. STONE

See also **Antarctic Peninsula; Belgian Antarctic *(Belgica)* Expedition (1897–1899); Bellingshausen, Fabian von; Biscoe, John; Charcot, Jean-Baptiste; de Gerlache de Gomery, Baron Adrien; French Antarctic *(Pourquoi Pas?)* Expedition (1908–1910); Nordenskjöld, Otto; South Shetland Islands; Swedish South Polar Expedition (1901–1904); Swedish South Polar Expedition: Relief Expeditions**

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FRENCH ANTARCTIC *(POURQUOI PAS?)* EXPEDITION (1908–1910)

Stimulated by the success of his earlier expedition aboard *Français,* Jean-Baptiste Charcot resolved on continuing the exploration of the Antarctic Peninsula. He intended to study the area "in all branches of science" and "to verify, complete and expand" the work done on the earlier expedition. One of the aims of the *Français* expedition had been to determine whether Antarctica was a continent or a group of ice-covered islands. The achievement of this had been frustrated when *Français* struck a rock in January 1905, necessitating a return northwards due to a continual flow of water entering the ship. Charcot regarded these goals as unfinished business to be resolved by a second expedition.

Charcot submitted his plan to the Academy of Sciences and secured its approval and this, together with the approval of various other official French organisations, made the endorsement of the government itself, and its financial backing, almost inevitable. Charcot was thus able to secure substantial funding, so that the expedition was lavishly equipped, certainly more so than most of those of the Heroic Age of Antarctic exploration.

Français had been sold to the Argentine government, and Charcot determined, after various attempts to purchase a whaler, to commission another vessel from the same shipbuilder, Gauthier of Le Havre, that had constructed his earlier ship. The new vessel was the fourth one that he had owned with the name *Pourquoi Pas?*. She was launched on May 18, 1908, a three-masted barque constructed to the highest standards. She was immensely strong, with very close ribs and several layers of planking, and came equipped with a powerful 450-hp engine, which was installed as a result of *Français*'s having been so underpowered.

The expedition left Le Havre on August 15, 1908, and of the twenty-two members of the expedition, no fewer than eight had served aboard *Français,* a clear indication of Charcot's ability as a leader. Proceeding via Rio de Janeiro and Buenos Aires, the ship left Punta Arenas on December 16, and after a rapid transit of the Drake Passage (Charcot seems to have been extremely fortunate in his navigations in that notorious area) it arrived at Smith Island 6 days later. They sailed directly to Deception Island, where Norwegian whalers were already established, and on December 29 reached Booth Island and the bay in which *Français* had wintered in 1904. On January 1, 1909, Charcot discovered a wonderfully sheltered harbour, on nearby Petermann Island, which he named Port Circumcision. Almost immediately, Charcot set off by boat to explore the coastline to the east of Petermann Island, but uncharacteristically, insufficient supplies were taken, and in suddenly deteriorating weather and rapidly forming ice, the situation quickly became serious. Only after 3 full days away did the party eventually reach the ship. This incident seems to have been one of Charcot's very few lapses in planning.

Soon after this, *Pourquoi Pas?* ran firmly aground. Fortunately, she floated off on the next high tide, but it was necessary to delay the progress of the expedition until the extent of the damage could be estimated. Although there was significant damage, the ship was strong enough that it was agreed the damage was not serious enough to hinder the continuation of the voyage. In mid-January a detailed examination and mapping of Adelaide Island was carried out, and they discovered a large gulf that was named Marguerite Bay after Charcot's second wife. They then approached to within 2 miles of the coast of Alexander Island before, short of coal, and with increasing ice, the ship returned to Port Circumcision to winter.

Charcot followed the same principles that had proven so successful on his previous expedition. Huts were built ashore for the scientific instruments and were lit by electricity. The narrow entrance of the harbour was secured by steel hawsers to prevent the ingress of icebergs, and the ship was roofed over with canvas. But it was his care for his men that most marked Charcot as a leader, and all possible measures, including the publication of a daily newspaper, were taken to prevent the onset of boredom and the inevitable consequent demoralisation.

Exploratory journeys away from the ship were made in September and October, and, after these, the ship left the harbour in November. She headed for Deception Island in order to replenish coal stocks. The opportunity was taken for a thorough survey of the condition of the exterior of the hull by a diver from the Norwegian whalers active there. The damage from the grounding turned out to have been severe but, despite this, Charcot determined to again head south. Hoping to reach Hope Bay, they were halted by ice, but did land the first two men ever on Bridgeman Island. They then visited Admiralty Bay at King George Island before returning to Deception. Turning back south on January 6, 1910, they made directly for Alexander Island, from offshore of which

Charcot was delighted to sight land to the southwest. This new island was ultimately named Charcot Island in honour of the explorer's father.

Charcot now headed west hoping to link his discoveries with those made by previous explorers. However, he was frustrated in his desire to explore the coastal areas as thoroughly as he wished to because of large amounts of sea ice. Nevertheless, on January 14, they spied Peter I Øy, the first time it had been sighted since Fabian von Bellingshausen's expedition almost 90 years earlier. Charcot then followed the coast westwards as far as 124° W. On January 22, Charcot decided that the work of the expedition had been completed and determined to return to South America. *Pourquoi Pas?* arrived at Punta Arenas on February 11, following which she underwent extensive repairs before proceeding to Rouen, which was reached on June 5.

The *Pourquoi Pas?* expedition confirmed Charcot's status as an explorer of the highest rank. The results were most impressive. In addition to the charting of some 1,250 miles of coastline in the difficult waters to the west of the Antarctic Peninsula, a very large amount of new scientific data had been secured—ultimately filling 28 volumes of scientific reports. Meanwhile, Charcot had maintained morale at the same high levels as those that had been evident on his earlier expedition, and despite the huge difficulties caused by the grounding of the ship, the programme of work had not been seriously affected. Charcot's aims in his expeditions were always modest. He himself noted that the Antarctic Peninsula, selected as the scene of his efforts, meant an approach to the South Pole was unlikely. More satisfying for Charcot was sailing his own vessel in unknown waters and facilitating research by scientific colleagues on board.

It is noteworthy that two of the sites in Antarctica most frequently visited by tourists, Port Lockroy and Port Circumcision, are closely associated with Charcot, and it is a matter for regret that so many go there without ever hearing his name.

IAN R. STONE

See also **Antarctic Peninsula; Bellingshausen, Fabian von; Charcot, Jean-Baptiste; Deception Island; French Antarctic *(Français)* Expedition (1903–1905); Peter I Øy; Russian Naval *(Vostok* and *Mirnyy)* Expedition (1819–1821); South Pole; South Shetland Islands; Tourism**

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FRENCH NAVAL (*ASTROLABE* AND *ZÉLÉE*) EXPEDITION (1837–1840)

Jules-Sébastien-César Dumont d'Urville made three voyages to the Pacific. The third was especially notable for its contribution to the exploration of the Antarctic.

Astrolabe, under the direct command of Dumont d'Urville, departed France in September 1837 accompanied by *Zélée,* commanded by Charles-Hector Jacquinot (1796–1879). Dumont d'Urville was one of France's experts on the Pacific, and the instruction, issued in August, that stated, "You will extend your exploration towards the Pole as far as the polar ice will permit" looks like an ill-considered afterthought. But in fact, the French had always been interested in the discoveries made by James Weddell, who had reached 74°15′ S. His account had been published in 1825, and this was the first occasion France had to emulate his achievements.

The French ships left the Straits of Magellan on 9 January 1840, the first drift ice was seen on the 13th, and icebergs were encountered from 15 January. Compared to Weddell's voyage, the French had a hard time of it, and on the 21st they met with a great barrier of ice, called *La banquise,* which during this season was to prevent them from sailing any farther south than 62°21′ S.

Dumont d'Urville's descriptions of the polar terrain have few rivals. When he wrote of "a new world unfolding before our eyes, but a world that is inert, mournful and silent, where everything threatens man with annihilation" (Rosenman 339), the style was self-conscious and romantic, but it also indicated the quickly earned respect he had for such a formidable environment. His words were complemented by the sketches of the artists on board, Ernest Goupil (1814–1840), who later died in Hobart, and Louis Le Breton (1818–1866).

The two ships soon became caught in the ice. Dumont d'Urville lamented "the tragic prospect of seeing my two crews forced to seek precarious shelter on the icebergs surrounding us, there awaiting, in despair and horror, an end to their pitiful existence"

(Rosenman 341), while, in fact, the men seem to have enjoyed the chance to skylark. Le Breton's painting of this, "The corvettes *Astrolabe* and *Zélée* caught in the ice, February 1838" (1841, Musée des Beaux-Arts, Quimper, France), is the best visual representation of Antarctic conditions in the prephotography era. In poor sea conditions, the expedition persisted for nearly 2 months. It was, wrote the commander, "a complete failure."

After being rebuffed by the ice, with many of the crew sick, the expedition sailed for Chile, then the more familiar waters of the Pacific, where the next 18 months were spent. The French had now resolved to make a second voyage to the Antarctic, via Hobart in Van Diemen's Land (Tasmania), which they reached on 12 December 1839. A week elapsed before Dumont d'Urville was able to meet the Governor of the English colony, Sir John Franklin (1786–1847). Franklin was, arguably, the world's foremost Arctic explorer, but the French commander was somewhat circumspect in recounting what advice Sir John may have conveyed.

The French left Hobart on New Year's Day, 1840. Dumont d'Urville's intentions were twofold. He wanted to "push down well south of Tasmania and determine under which parallel I would encounter pack ice" and "there was one important discovery yet to be made; the position of the magnetic pole."

On the 20th the crossing of the Antarctic Circle was celebrated, and late the following day Terre Adélie was claimed and named after the commander's wife, Adèle.

Returning to Hobart, on 29 January, 1840, a curious incident occurred that illuminates the tensions that existed between competing exploring nations. Dumont d' Urville was aware that the United States Exploring Expedition, under the command of Charles Wilkes, was in the region. That afternoon *Astrolabe* was approached by USS *Porpoise,* under the command of Lt. Cadwalader Ringgold, but before any communication took place, *Porpoise* tacked away. There had been a mutual misunderstanding, but it was a prickly breach of etiquette, and both later sought to excuse themselves. "We had not the slightest interest in keeping secret the results of our operation and the discoveries we had nearly paid for with our lives," claimed Dumont d'Urville (487), while Wilkes later wrote, "By refusing to allow any communication with him, he not only committed a wanton violation of all proper feeling, but a breach of the courtesy due from one nation to another" (Wilkes, vol. 11, p. 344).

Hobart was reached on 17 February 1840. A sketch by Aimé Desbois of the act of possession was given to Lady Franklin (now held in the Allport Library and Museum of Fine Arts, Hobart). The expedition returned to Toulon on 6 November 1840. Dumont d'Urville was killed in a railway accident, but his brilliant publication *Voyage au Pôle Sud et dans l'Océanie* was his legacy. France continued to venerate his memory by naming its contemporary Antarctic station, established in 1956, Dumont d'Urville.

The areas visited by Dumont d'Urville were not more fully explored until Douglas Mawson's Australasian Antarctic Expedition (1911–1914). And nearly 100 years elapsed before the limits of Terre Adélie—between Wilkes Land and George V Land—were formally defined as "The islands and territories situated south of the 60° parallel of south latitude and between the 136° and 142° meridians of longitude east of Greenwich."

MARTIN TERRY

See also **Australasian Antarctic Expedition (1911–1914); Dumont d'Urville, Jules-Sébastien-César; Mawson, Douglas; United States Exploring Expedition (1838–1842); Weddell, James; Wilkes, Charles**

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FUCHS, VIVIAN

Sir Vivian Fuchs was a British Antarctic explorer who led the first expedition to cross Antarctica, and served for more than 20 years as director of Britain's national Antarctic program.

Vivian Ernest Fuchs was born on February 11, 1908, the only child of a prosperous German father and Anglo-Australian mother. During World War I his father was interned and his income severely curtailed, leaving young Fuchs to be brought up in genteel poverty by his partly disabled mother. The return of peace brought reunion to the family and the gradual restoration of its fortunes. Fuchs attended Brighton College as a boarder, and in 1926–1930 was an undergraduate at St. John's College, Cambridge, where he read geology and natural history. His first expedition was with a summer vacation climbing party in East Greenland, organized by his geology tutor, J. M. Wordie, who had served in Sir Ernest Shackleton's *Endurance* expedition of 1914–1917. Later he met Louis Leakey and E. Barton

Worthington, with whom he was to serve as a field geologist on three African expeditions—to the East African Lakes (1930–1931), to Olduvai Gorge (1931–1932), and to Njorowa Gorge (1933). Now interested in both geology and anthropology, he subsequently led his own African expeditions to Lake Rudolf in 1934 and Lake Rukwa in 1937–1938.

In 1933 Fuchs married his cousin, Joyce Connell, who shared his interest in travel and adventure. In 1936 the couple settled in Barton Road, Cambridge, which remained their home base throughout their lives. In the same year Cambridge University awarded him a Ph.D. With World War II looming, in 1938 he joined the Territorial Army, and in 1939 was commissioned in the Cambridgeshire Regiment. He saw wartime service in West Africa in 1942–1943 and, after undertaking a staff course, served from 1944 with the Second Army in Europe, where he was mentioned in dispatches. He ended the war as a town major in Civil Affairs in Plön, Schleswig-Holstein.

Released from the army in 1946, Fuchs returned to a growing family (Hilary, born 1936, and Peter, born 1940). Hoping to continue working as a field geologist, he sought to join the Falkland Islands Dependencies Survey (FIDS), an expedition of seven bases in the British (South American) sector of Antarctica. Originally "Operation Tabarin," a wartime naval operation, FIDS had recently been taken over by an unprepared and reluctant Colonial Office. To his surprise, Fuchs was invited to join as expedition leader, and was briefed by the controlling committee to develop a scientific field programme that would help to justify the continuing operation of bases in Antarctica.

Between early 1948 and 1950 Fuchs led the survey from Base E, Stonington Island, Marguerite Bay, where he quickly acquired skills of dog-driving and ice-craft. Frustrated in his original plans by the non-arrival of a promised aircraft, he nevertheless led a year's vigorous programme of sledging and surveying in southern Marguerite Bay and George VI Sound. In early 1949, when he and his ten companions were due for relief, persistent sea ice prevented the resupply ship *John Biscoe* from entering Marguerite Bay. "The Lost Eleven," as they became known to the outside world, completed a further involuntary year, in which Fuchs continued to supervise by radio the work at the other bases, and led extensive geology-oriented sledging journeys southward from Base E.

On his return to Britain in early 1950, Fuchs was retained by the Survey to establish and direct the FIDS Scientific Bureau—essentially to develop a long-term programme of scientific research that could be maintained from an increasing number of permanent stations in the British sector—on the Antarctic Peninsula, the South Orkney Islands, South Shetland Islands, and South Georgia. However, during his stay on Stonington Island, Fuchs had begun to plan an expedition, previously attempted by Wilhelm Filchner in 1911 and Ernest Shackleton in 1914, to cross Antarctica from the Weddell Sea to the Ross Sea. As this was well beyond anything that could be done within the remit of FIDS, in April 1955 he took leave from the Scientific Bureau to plan and set up his own Commonwealth Trans-Antarctic Expedition. Although opposed by almost the entire UK polar establishment, he gained support from the Treasury, the Royal Geographical Society, the governments of New Zealand, Australia, and South Africa, and private subscriptions.

Leaving Britain in November 1955, he established Shackleton Base on the Weddell Sea coast, leaving a wintering party to complete the base. In the following spring he returned to explore inland and set up an advance base (South Ice) by air 450 km inland. After wintering at Shackleton in 1957, he began the crossing. Using dog teams, Muskeg tractors, Sno-Cats, and aircraft, he and his party crossed the continent from Shackleton to Amundsen-Scott, the recently established US scientific station at the South Pole. There the team was met by a New Zealand support party led by Sir Edmund Hillary, and returned with them to Scott Base in McMurdo Sound.

On returning to London in 1958, Fuchs was knighted, and the following year he returned to FIDS as director. He continued to develop and increase the scientific efficiency and output of an expanding Survey, touring the stations every second or third year. From 1961, when Britain joined the Antarctic Treaty, FIDS was renamed the British Antarctic Survey (BAS), and from 1967, still under his direction, it was taken under the wing of the recently formed Natural Environment Research Council. Sir Vivian retired from the directorship in 1973.

In 1974 Fuchs was appointed FRS. Through a long retirement, with membership in many learned societies, he remained active in an advisory capacity in polar, geographic, and scientific affairs. In 1982–1984 he was appointed president of the Royal Geographical Society, an organization that had supported both his African and his Antarctic expeditions, and awarded him two of its most prestigious medals. He wrote a history of FIDS and BAS *(Of Ice and Men)*, and later his autobiography *(A Time to Speak)*. Widowed in 1990, he later married Eleanor Honnywill. He died on November 11, 1999.

Bernard Stonehouse

See also **British Antarctic Survey; Commonwealth Trans-Antarctic Expedition (1955–1958); German South Polar *(Deutschland)* Expedition (1911–1912);**

Hillary, Edmund; Imperial Trans-Antarctic Expedition (1914–1917); International Geophysical Year; Wordie, James

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FUNGI

The kingdom Fungi is a large, diverse group ranging from simple yeast cells to complex fruiting bodies (typical mushrooms and bracket fungi), and in some cases to diffuse colonial organisations that may exist over wide areas. Approximately eighty thousand species of fungi have been named, and it has been suggested that more than one million species may be currently undetected or undescribed. While the most evident Antarctic fungi are those forming lichens with symbiotic photosynthetic cyanobacteria and algae, only the nonlichenized fungi are considered here.

At least 870 species of fungi have been reported from within the Antarctic Polar Front. Possibly the most southerly record for a true "mushroom" is a probable *Gallerina* species on Léonie Island (67°36′ S). In general, macrofungi and most basidiomycetes are confined to the sub-Antarctic and the Antarctic Peninsula. Microfungi, particularly ascomycetes and zygomycetes, and yeasts have been isolated from all Antarctic areas. There is little evidence for endemism, and less than 10% of the species reported have been described as new, while many have also been recorded from Arctic and mountain regions, suggesting that species are more associated with particular environments than with geographical regions. There is considerable uncertainty over which fungi are indigenous to the Antarctic. Some reports have suggested that species have been introduced by human activity, but there are comparatively few background assessments to demonstrate this. Viable fungal propagules have been reported from sea and fresh water, soil, air, and ice-core samples, and these may provide a continual source for colonisation.

The function of fungi within Antarctic ecosystems remains largely unknown. Plant pathogens have been identified from the sub-Antarctic, as have nematode and other invertebrate pathogens, parasites, and predators, and a small number of potentially pathogenic species have been isolated from birds. Similar species and associations have been reported from maritime and continental Antarctica. Some fungi form mycorrhizal associations with plants, and although this has been observed in the sub-Antarctic, there has been debate as to whether mycorrhizas occur further south. Recent studies have identified novel potentially mycorrhizal associations on the Antarctic Peninsula between the ascomycete fungus *Hymenoscyphus ericae* and the liverwort *Cephaloziella exiliflora,* and between the zygomycete *Glomus antarcticum* and the grass *Deschampsia antarctica*.

Many fungi may be present in the Antarctic as transient or dormant propagules, while some that are usually associated with specific hosts in other regions may have adapted to alternative lifestyles. One example is the ascomycete *Lecanicillium lecanii*. This is normally an insect pathogen, but in Antarctica it has been isolated together with bacteria and algae from mineral crusts.

There is little information regarding Antarctic marine fungi. Some baiting experiments have been conducted in coastal waters, and yeasts have been isolated from the open ocean, but few, if any, true marine fungi have been reported.

A major constraint to the identification of fungi is that less than 20% of known species have been isolated and grown in pure culture, and of these, many require specific isolation conditions and media. New molecular studies suggest that there may be many more fungi present in the Antarctic environment, although further consideration will need to be given to their ecological role.

PAUL BRIDGE

See also **Algae; Antarctic Peninsula; Liverworts; Polar Front**

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GENE FLOW

Gene flow is a process occurring between two or more populations of a species and is defined as the movement of genes from the gene pool of one population to the gene pool of another population. The movement of genes between populations may occur through the migration of individuals (or zygotes), or through the movement of gametes.

The most important genetic effect of gene flow is the homogenization of the genetic composition of different populations, which tend to be genetically more similar to each other along with the increase of gene flow. By homogenizing gene frequencies across populations, gene flow counteracts their differentiation by random genetic drift and, in some cases, selection.

When gene flow is determined by moving individuals, it exerts its effects only if the migrating individuals will eventually reproduce in the new population, therefore introducing their genes into the new gene pool. Individuals may actively move from one population to the other, and highly mobile species have higher levels of gene flow. However, they can also be passively transported by other animals or by physical agents (such as water currents or winds). Passive transport is also responsible for the migration of seeds and spores, as well as pollen grains in terrestrial plants or gametes in marine animals and plants, which also contribute to the enhancement of gene flow.

In population genetics, gene flow can be estimated using direct or indirect methods. Direct methods are based on the release and recapture of marked individuals. Indirect methods are much more widely used and are based on the assessment of gene frequencies in different populations and the estimate of gene flow from levels of interpopulation differentiation.

Levels of gene flow play an important role in speciation, as new species arise only when gene flow is insufficient to counteract the differentiation between allopatric populations. Therefore, a prerequisite for speciation is the interruption (by any method) of gene flow between populations.

Antarctic soil invertebrates, such as springtails, mites, and nematodes, show a fragmented distribution, resulting in isolation between populations being enhanced by the presence of large areas of soil where survival is impossible. Therefore, gene flow might be strongly reduced, and populations tend to have higher levels of genetic differentiation compared to those observed in related species inhabiting temperate habitats. Due to the low vagility of these organisms, active migration between populations is negligible, although moderate levels of passive transport may be determined by wind or soil trapped in the feet of birds. The reduction of gene flow determined by the peculiar environmental conditions of Antarctic soils may provide suitable conditions to promote speciation.

Passive dispersal of propagules by means of wind or water flowing in small streams might guarantee higher levels of gene flow in moss species, which appear to be genetically more homogeneous than soil invertebrates.

Interestingly, significant levels of genetic differentiation have been found also in marine organisms, such as krill, suggesting that interruption or reduction of gene flow can be caused by marine currents.

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See also **Adaptation and Evolution; Biodiversity, Terrestrial; Colonization; Ecosystem Functioning; Marine Biology: History and Evolution; Mosses; Nematodes; Parasitic Insects: Mites and Ticks; Soils; Springtails**

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GENTOO PENGUIN

The gentoo penguin *Pygoscelis papua* is a tall penguin that weighs approximately 5–5.5 kg. It is black dorsally with white underparts. The head is black with a prominent triangle of white feathers above each eye. The iris is brown and there is a white ring around the eye. The bill (with black culmen and tip), legs, and feet are orange to red.

Gentoo penguins walk with their flippers raised behind the body. The birds wade into water until their flippers are half-submerged, then swim. On return, they porpoise towards their breeding locality, survey it, and then swim quickly ashore. On icy coasts, they leap out of water onto the ice.

Distribution

The gentoo penguin occurs in sub-Antarctic and Antarctic waters, usually between about latitudes 45° and 65° S. It is one of three penguins in the genus *Pygoscelis*. It has a more northerly distribution than the other two species, the Adélie *P. adeliae* and chinstrap *P. antartica* penguins, although there is some overlap in breeding ranges in the South Atlantic region.

The gentoo penguin breeds on ice-free ground at the Antarctic Peninsula, and at Antarctic and sub-Antarctic island groups in the Atlantic (Falkland, South Shetland, South Orkney, South Georgia, South Sandwich), Indian (Prince Edward, Crozet, Kerguelen, Heard), and Pacific (Macquarie) Oceans. A few pairs breed in the Beagle Channel at the southern tip of South America.

Annual Cycle

Some adult birds remain near their colonies throughout the year unless ice conditions force them to move to ice-free areas offshore. However, numbers at colonies during the nonbreeding period are much reduced and birds may be absent from the colony for up to 5.5 months after moult. At southern localities, birds disperse from their colonies in autumn after moult. Upon return to colonies, birds may fast for a short period (1–5 days). The courtship period (from pair formation to clutch completion) lasts about 25 days.

Laying is earliest at the northern localities, commencing about mid-June and peaking in late June or July, and progressively later southwards. At the South Orkney Islands and the Antarctic Peninsula, laying occurs in November. At the northernmost localities, the laying period extends over 5 months, although more than 80% of pairs initiate laying within a period of 3 weeks. South of the Polar Front, laying is more synchronous. At South Georgia, 95% of clutches are begun within a period of about 2 weeks.

Both birds feed regularly during courtship and incubation, although the female may go to sea for 1–3 days between the laying of eggs, leaving the male alone. Incubation is by both parents, starts in earnest once the second egg is laid, and takes 35–36 days. The fledging period lasts 74–100 days. Chicks are normally fed each day and their mass increases approximately linearly during the first 70 days after hatching.

Birds moult annually at the conclusion of breeding. They leave breeding localities to fatten up at sea for 10 days to 2 months before moulting ashore. They replace all their feathers during a fast of about 20 days.

Breeding and Survival

Gentoo penguins are monogamous, with often long-lasting pair bonds. They breed in small to large colonies; nests may be more than 1 m apart. There is usually fidelity to nest sites, but locations of colonies may be changed between years. Nesting areas are flat or gently sloping. Nests are scraped-out hollows, built with stones, shells, bones, feathers, and vegetation; nesting materials are sometimes stolen from neighboring nests. The male initiates nest construction, which the female continues, after pair formation, with material brought by the male.

Gentoo penguins normally lay clutches of two similarly sized eggs, with the interval between laying 3–4 days. At northern localities, if clutches are lost they may be replaced 1–2 months later. The first chick to hatch is noticeably larger than the second. At colonies on the Antarctic Peninsula, both chicks may fledge. At the northernmost breeding localities, it is rare for more than one chick to survive, and breeding success is typically lower than at localities farther south.

Gentoo penguins may breed when 2 years old, but usually will not do so until 3 years. When food is scarce, or following severe winters, mortality may increase, substantial numbers of birds may not breed, fidelity to mates may decrease, and breeding may be delayed. At Marion Island, delayed onset of breeding led to high mortality being inflicted on eggs and small chicks by returning sub-Antarctic skuas *Catharacta lonnbergi*. Annual survival of adults is about 85%, and of birds in their first year 27%–59%.

Food and Feeding

Gentoo penguins feed during the day, catching prey by pursuit diving. At South Georgia, Antarctic krill *Euphausia superba* is their main prey, but fish are also eaten. Most krill is caught on dives shallower than 54 m, whereas most fish are taken at 54–134 m. At northern localities, crustaceans and cephalopods are eaten, but benthic and midwater fish dominate the diet. While breeding, gentoo penguins have a maximum foraging range of about 100 km, but they usually feed much closer to breeding localities than this.

Population Size

The overall population of gentoo penguins is thought to be about 317,000 pairs, of which approximately 25% occur at the Antarctic Peninsula and 75% at sub-Antarctic islands. The largest populations are at the Falkland Islands (115,000 pairs) and South Georgia (105,000 pairs).

Conservation Status

The gentoo penguin is classified as Lower Risk/Near Threatened on the Red List of IUCN (The World Conservation Union). Most populations around the Antarctic Peninsula have increased. However, populations at several sub-Antarctic localities have decreased. That at Bird Island, South Georgia decreased by 20% from about 1985–2005 and that at Marion Island by 40% from 1994–2005. The latter decrease likely resulted from scarcity of food, thought attributable to climate change. At South Georgia, when krill was scarce, meal size, rates of provisioning of offspring, and breeding success decreased by 90%. At the Falkland Islands, there was a decrease from about 110,000 pairs in the 1980s to 65,000 in the mid-1990s, followed by a recovery to present levels equivalent to those of the 1980s.

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See also **Adélie Penguin; Antarctic Peninsula; Birds: Diving Physiology; Chinstrap Penguin; Crozet Islands (Îles Crozet); Heard Island and McDonald Islands; Kerguelen Islands (Îles Kerguelen); Macaroni Penguin; Macquarie Island; Penguins: Overview; Polar Front; Prince Edward Islands; South Georgia; South Orkney Islands; South Sandwich Islands; South Shetland Islands; Zooplankton and Krill**

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GEOLOGICAL EVOLUTION AND STRUCTURE OF ANTARCTICA

Like all other continents, Antarctica has "very old" cores or nuclei, generally called cratons, that are roughly surrounded by successively younger (mountain) belts. These belts are the products of plate-tectonic events such as the subduction of oceanic crust beneath continental crust and/or the collision of two former separate continents. More precisely, these mountains belts, or "orogens," are the products of convergent plate-tectonic movements and form at or near the margin of (former) plates. These convergent movements are complemented by divergent plate-tectonic movements that divide continents, forming rifts, grabens, and finally oceans.

Therefore, it is reasonable to discuss together the geological structure and evolution of Antarctica chronologically from the oldest to the youngest.

Continental nuclei or cratons are those parts of the continents that are older than 1500 million years; the "younger" Antarctic mountains belts (orogens) are as follows:

- 1300 to 900 Ma: the orogens of Grenvillian age,
- 600 to 500 Ma: the Ross and the Pan-African orogens,
- 250 to 200 Ma: the Ellsworth or Weddell Orogen,
- 150 to 90 Ma: the Antarctic Andean Orogen,
- 50 Ma to recent: the plate-tectonically active part of Antarctica.

In contrast to all other continents, Antarctica and its rocks, and thus its geological structure and history, are more than 99% covered by ice, which is up to 4700 m thick. This means that geological knowledge of Antarctica is based on less than 1% of the continental area. This 1% has not been fully investigated everywhere, but about half of the 99% has been surveyed remotely by geophysical techniques, mainly by aeromagnetic and gravimetric surveys. Therefore, our understanding of Antarctica's geological structure and history will change and improve in the future.

The Antarctic Cratons

Until the early 1980s, the "East Antarctic Shield" was assumed to be a single and uniform Antarctic craton, but this term is incorrect for two reasons:

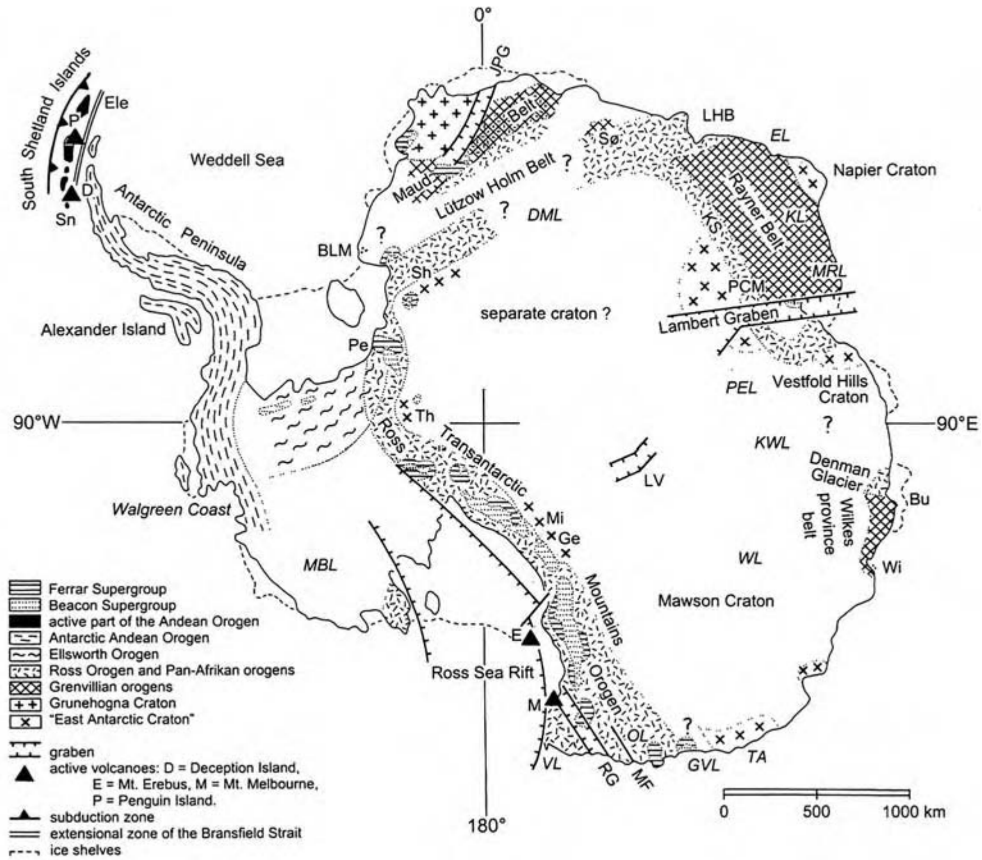
1. A craton comprises two parts: a basement and an undeformed, relatively young cover. That part of the craton where the older basement crops out is called the "shield" and that part where undeformed sedimentary rocks cover the basement is called the "platform." Even if East Antarctica was one uniform craton, it would be a "platform" with some minor "shields," as it is covered, for the most part, at least, by the "rock" ice!
2. East Antarctica comprises several cratons, at least two of which are widely accepted: the Grunehogna Craton and the East Antarctic Craton *sensu stricto* (that is, in the strictest sense).

The Grunehogna Craton

The small Grunehogna Craton (sometimes also called the Maudheim Craton) comprises westernmost Dronning Maud Land. There, sediments older than 1000 million years are flat-lying and undeformed. The even older (around 3000 million years) basement crops out only at Annandagstoppane (c. 6° W, 72°30′ S), where it is correctly termed a "shield."

The East Antarctic Craton Sensu Stricto

The larger of the Antarctic cratons, the East Antarctic Craton *sensu stricto,* occupies the larger part of East Antarctica beyond the Transantarctic Mountains (i.e., west of the Transantarctic Mountains in Victoria Land, south of them in their central and southern sections, and east of them at their "Atlantic end" at the Pensacola Mountains). The East Antarctic Craton emerges from beneath the East Antarctic ice sheet in



The geological structure of Antarctica. BLM: Bertrab, Littlewood, Moltke nunataks, Bu: Bunger Hills, Ele: Elephant Island, Ge: Geologists Range, JPG: Jutul–Penck Graben, KS: Kuunga Suture, LHB: Lützow-Holmbukta, MF: Matusevich strike-slip fault, Mi: Miller Range, PCM: Prince Charles Mts., Pe: Pensacola Mts., RG: Rennick Graben, Sh:Shackleton Range, Sn: Snow Island, Sø: Sør Rondane, Th: Thiel Mts., Wi : Windmill Islands, DML: Dronning Maud Land, EL: Enderby Land, GVL:George V Land, KL: Kemp Land, KWL: Kaiser Wilhelm II. Land, MBL: Marie Byrd Land, MRL: Mac.Robertson Land, OL: Oates Land, PEL: Princess Elizabeth Land, TA: Terre Adélie, VL: Victoria Land, WL: Wilkes Land.

only a few places, that is, the southern Shackleton Range, the eastern Thiel Mountains, the Miller and Geologists ranges of the central Transantarctic Mountains and near the continental margin in Enderby Land, in the southern Prince Charles Mountains, in the Vestfold Hills, in Wilkes Land, in Terre Adélie, and in George V Land. The exposed basement of the craton (shield) consists of high-grade metamorphic rocks, such as gneiss and granulite complexes, which yield radiometric ages from more than 1500 million years to more than 3500 million years (Enderby Land). Occasionally, the basement is more or less covered by platform sediments. An almost-flat-lying sequence of sedimentary rocks of Neoproterozoic, Cambrian, or Ordovician age occurs in the Thiel Mountains. In the southern Shackleton Range, relics of internally undeformed Neoproterozoic sediments with an autochthonous Neoproterozoic regolith at their base cover locally the 1600-million-year-old crystalline basement complex. In George V Land, the boundary to the next-youngest unit, the Ross Orogen, is not clear and is still debated. Here the cratonic basement ("shield": up to 2440-million-year-old granulites, gneisses, and related rocks) borders abruptly much younger granites (c. 500 million years old) to the east in the form of a shear zone.

Parts of Enderby, Kemp, and Mac.Robertson lands have been separated from the East Antarctic Craton and attributed to younger orogenic belts, that is, the Grenvillian and Pan-African belts (in the broadest sense) (Boger et al. 2001; 2002; Boger and Miller 2004; Fitzsimons 2000a), so that northern Enderby Land is considered to be a separate craton (Napier Complex).

The same could happen farther east, when the southern extensions of the Grenvillian and Pan-African orogenic belts in the Denman Glacier region, at Bunger Hills and on the Windmill Islands (Wilkes Land) (Fitzsimons 2000a, b) under the ice sheet, are known more precisely. Then the Vestfold Hills, together with the major parts of Princess Elizabeth and Kaiser Wilhelm II lands, may also be regarded as a separate craton.

Thus, in the next few years, the East Antarctic Craton could change its configuration drastically and appear to be an accumulation of several much smaller cratons, which may be

- the already accepted Grunehogna Craton, which is actually a fragment of the African Kalahari Craton
- the Napier Craton, which is actually a fragment of Dwarhai Craton in India
- the Vestfold Hills Craton
- the Mawson Craton (Fitzsimons 2000a, 2003), possibly comprising the Miller and Geology ranges of the central Transantarctic Mountains, the shield areas of eastern Wilkes Land, Terre Adélie, George V Land, and their Australian counterpart, the Gawler Craton
- a craton comprising the southern Prince Charles Mountains, the southern Shackleton Range, and perhaps the eastern Thiel Mountains

The relationships between the Mawson Craton, the Vestfold Hills Craton, the southern Shackleton Range, and the southern Prince Charles Mountains are totally unknown and wide open to speculation. Furthermore, the cratonic areas could even be subdivided if, for example, the 1600- to 1700-million-year-old orogens can be separated.

The Orogenic Belts of Grenvillian Age

Although Grenvillian strictly means an orogeny at 1100 Ma in eastern North America, Grenvillian in the broader sense is used in the geodynamic and Antarctic literature to refer to the event that resulted in the formation of the supercontinent Rodinia in Mesoproterozoic/Neoproterozoic times (i.e., about 1300 to 900 Ma). Whereas the Pre-Rodinian oceanic crust has been consumed by this process, at least parts of the Pre-Rodinian continents have survived in the cratons. The evidence for this event is the orogenic mountain belts at the former plate margins. In Antarctica, there are three (Fitzsimons 2000a):

1. It is generally accepted that the Maud Belt of Dronning Maud Land is the trace of the welding together of the Grunehogna Craton and the Shackleton Range/southern Prince Charles Mountains craton. It extends from western to central Dronning Maud Land and includes Heimefrontfjella, Kirwanveggen, H.U. Sverdrupfjella, Mühlig-Hoffman-Gebirge, Wohlthatmassivet, Schirmacheroasen, and possibly parts of the Sør Rondane.
2. The Rayner Belt (Yoshida and Kizaki 1983) in Enderby, Kemp, and Mac.Robertson lands connects the cratons of the Napier Complex and the southern Prince Charles Mountains and has been identified in the northern Prince Charles Mountains and the Rayner Complex (Boger et al. 2002).
3. The Wilkes province belt (Fitzsimons 2000a) of Wilkes Land occurs in the Bunger Hills and Windmill Islands and merges the Vestfold Hills and the Mawson cratons.

As their structures (polyphase folding), metamorphism (gneisses, granulites), and magmatism (granitoids) somewhat resemble those in the cratons, those areas that formed during the Grenvillian orogeny have been included in the cratons.

In the late 1980s and early 1990s, the Antarctic Grenvillian orogen was assumed to be a very long, single event, following the Antarctic coast as a 250-km-wide strip from Coats Land in the west to George V Land in the east. This has also occasionally been called the "Circum East Antarctic Mobile Belt" (Yoshida 1992). Such an extension is incorrect for Terre Adélie and George V Land and is unproven for Coats Land. There the only outcrops are three small groups of nunataks called Littlewood, Bertrab, and Moltke nunataks. The Littlewood and Bertrab nunataks consist of rhyolite and granophyre yielding an age of 1100 million years (Storey et al. 1994), but they are absolutely undeformed. However, an orogen cannot be inferred just from the existence of rhyolites of the right age. The Moltke nunataks could prove crucial but, unfortunately, they have been inaccessible since their discovery in 1911–1912 because of overhanging ice masses. However, some fearless explorers collected a few samples and confirmed that there is no rhyolite, but the structural and age data are still missing (Kleinschmidt 2002).

The Ross Orogen

Roughly 750 Ma, Rodinia started to disintegrate, and oceans opened between the numerous fragments. Also, the area of present-day East Antarctica was broken apart (West Antarctica did not exist at that time). The southern prolongation of the Mozambique Ocean opened between the Grunehogna Craton and the rest of East Antarctica as shown by relics of this ocean (ophiolite) in the northern Shackleton Range. Presumably, there was a branch of this ocean in the area of southern Enderby Land extending from the Prince Charles Mountains towards Princess Elizabeth Land. At about the same time, the edge of the Palaeo-Pacific Ocean formed in the general area of the present Transantarctic Mountains. Subduction of the Palaeo-Pacific beneath East Antarctica resulted in the Ross Orogen around 600 to 500 Ma. Therefore, the Ross Orogen *sensu stricto* is restricted to the Transantarctic Mountains (Stump 1995) and extends from northern Victoria Land at the Pacific end up to the Pensacola Mountains at the Atlantic end. Westernmost Marie Byrd Land (Edward VII Peninsula) has to be included within the same orogenic belt, as it separated only much later, towards the end of the Cretaceous.

The Ross Orogen is characterized by folds, thrusts, metamorphism, granitoids, terranes, and flysch- and molasse-type sediments. Remarkable thrusts have been reported from Oates Land that could be traced into the Australian continuation of the Ross Orogen, the Delamerian Orogen (Flöttmann et al. 1993). The systematic distribution of high- and low-pressure types of metamorphism (Talarico et al. 2004) and of S- and I-type granitoids (e.g., Vetter and Tessensohn 1987) led to the model of East Antarctic–ward subduction of the Palaeo-Pacific. In northern Victoria Land, the Ross Orogen comprises three so-called terranes: high- to medium-grade metamorphic rocks and granite dominate the Wilson Terrane to the west; the low-grade turbiditic Robertson Bay Terrane lies to the east; and the low-grade and volcanic-rich Bowers Terrane lies between these two. These terranes are considered to be allochthonous or just a related island arc (Bowers Terrane) and an accretionary wedge (Robertson Bay Terrane). All results indicate that the Ross Orogen is subduction dominated (Andean-type) with a partly oblique and partly orthogonal compressional regime.

The Other Orogens of Pan-African Age

Three orogenic belts formed at about the same time as the Ross Orogen during the Pan-African period of 600 to 500 Ma:

1. The belt of the Shackleton Range–Dronning Maud Land–southern Sør Rondane–Lützow-Holmbukta region. Jacobs et al. (1998) proposed the name "East Antarctic Orogen" or "East Antarctic Belt," while Fitzsimons (2000b) proposed the more appropriate "Lützow-Holm Belt."
2. The belt of the southern Prince Charles Mountains–Grove Mountains was called the "Kuunga Suture" (Boger et al. 2002).
3. The Denman Glacier region (Fitzsimons 2000b).

However, the exact extent of these orogens is uncertain because of their predominant ice cover, which is particularly true of the Denman Glacier belt.

The Lützow-Holm Belt is characterized by extensive thrust and nappe tectonics (Shackleton Range), by widespread and distinct late-orogenic collapse structures (Shackleton Range), by thick molasse formations (Blaiklock Glacier Group, Shackleton Range, Urfjell Group, Dronning Maud Land), and by syn- and post-orogenic magmatism (Dronning Maud Land) (Paech 2004). Therefore, these Antarctic portions, formed during the late Neoproterozoic to Cambrian, show typical characteristics of a collisional orogen.

The three belts indicate the amalgamation of West Gondwana (South America, Africa, and Grunehogna Craton) and East Gondwana (India, Australia, and main East Antarctica). As proposed by Boger et al. (2001, 2002), Gondwana's amalgamation may have taken place in two stages, the first before 550 Ma and the second after 550 Ma. The first step is merging West Gondwana and "Indo-Antarctica" (i.e., India and the northern Prince Charles Mountains plus the Napier Complex) manifested as the Mozambique Belt and as its Antarctic prolongation, the Lützow-Holm Belt. The second stage is adding the rest of East Gondwana (i.e., the rest of East Antarctica and Australia), and thus producing the Kuunga Suture. This idea could explain the discrepancy within the Lützow-Holm Belt and its "double-track": in Dronning Maud Land it is mainly older than 550 million years and thus part of the first stage. The Shackleton Range belongs to the second stage (<550 million years old). Thus, the existence of an old alien element between both "tracks," consisting of the Bertrab, Littlewood, and Moltke nunataks in southern Coats Land, is perfectly explicable, maybe as an exotic terrane or maybe a mini-craton.

The relation of the Denman Glacier belt, which is interpreted as a prolongation of the Leeuwin Complex of the Pinjarra Orogen in Australia, is still unclear.

During the Lifetime of Gondwana

The Pan-African orogenies led to the formation of the supercontinent Gondwana, existing from c. 500 Ma until 180 Ma. Its central part, that is, its keystone, was (East) Antarctica. Evidence for the existence of Gondwana's huge landmass is shown by the terrestrial sedimentary rocks that, in Antarctica, are collectively termed the "Beacon Supergroup," unconformably overlying the older formations of the cratons, and the Grenvillian and Pan-African orogenies.

The Beacon Supergroup occurs in the Transantarctic Mountains (Victoria Land, central Transantarctic Mountains, Pensacola Mountains), George V Land, the eastern edge of the Shackleton Range, north and south of the Shackleton Range (the Theron Mountains and Whichaway Nunataks respectively), western Dronning Maud Land, the Ellsworth Mountains, and Mac.Robertson Land (Lambert Glacier area). The main rock types are fluvial sandstones, indicating a predominantly terrestrial environment, that were deposited from Devonian through to Triassic times. The most conspicuous strata are Permo-Carboniferous tillites and diamictites combined with striations and Permian coal measures. These indicate a rather rapid climatic change from an ice age to dense woodlands, from cold conditions to humid conditions and mild temperatures (e.g., Collinson et al. 1994).

The Beacon Supergroup corresponds to the (lower) Gondwanan strata of India and South America, to the Karoo Supergroup of southern Africa, and to the Permo-Triassic analogues of Australia.

Gondwana Breakup

The disintegration of Gondwana started with rifting of the Gondwanan crust around 200 to 180 Ma. This initial rifting led to an intense Gondwana-wide Jurassic volcanism (c. 180 Ma), called the Ferrar Supergroup in Antarctica. These subalkaline, basic volcanic rocks are widespread in western Dronning Maud Land, in the vicinity of the Shackleton Range (Theron Mountains), throughout the Transantarctic Mountains from Pensacola Mountains to northern Victoria Land, and in George V Land.

The rocks of the Ferrar Supergroup form extensive flood basalt sheets (e.g., Kirkpatrick Basalt) or (more frequently) they occur as horizontal or subhorizontal sills (Ferrar Dolerites) intruded into older rock sequences (basement, Beacon Sandstone) where they can attain a thickness of a few hundred metres.

Although their chemistry is not an alkaline type, they are generally regarded as an indication of crustal extension (i.e., of Gondwana's decay) (Elliot 1992). However, they are also discussed in relation to the subduction processes of the Ellsworth Orogen.

The breakup of Gondwana, actually the separation of New Zealand from Marie Byrd Land, in the Cretaceous (some 100 Ma), is also accompanied by magmatism. Anorogenic A-type granites, the so-called "Byrd Coast Granites," formed on both Gondwanan fragments. The end of the Gondwana decay, and the consequent final isolation of Antarctica, was the opening of the strait between Victoria Land and Tasmania c. 35 Ma and of the Drake Passage between the Antarctic Peninsula and South America c. 25 to 20 Ma.

The Ellsworth or Weddell Orogen

The Pacific margin of Antarctica has existed since the formation of Gondwana and it was also the Pacific margin of Gondwana throughout Gondwana's existence. At this margin, the next growth zone of Antarctica, after the Ross Orogen, was added some 250 to 200 Ma. This is the Ellsworth Orogen, sometimes called the Weddell Orogen, or in a larger context the Gondwanides Orogen, which includes its continuation to southern Africa (Cape Fold Belt) and to South America (Sierra de la Ventana Fold Belt). The Ellsworth Orogen extends from the Ellsworth Mountains to the Pensacola Mountains and includes the Whitmore Mountains to the south. The chain of the Ellsworth–Pensacola Mountains represents the fold belt, while the Whitmore Mountains represent the magmatic arc of an Andean-type orogen. It merges with the Ross Orogen in the Pensacola Mountains, where it partly overprints the older structures of Ross age.

The Ellsworth Orogen trends noticeably obliquely to the Palaeo-Pacific margin of Antarctica indicated by the Ross Orogen. This obliqueness is due to secondary rotation, as demonstrated by palaeo-magnetic investigations by Funaki et al. (1991) and confirmed by Randall et al. (2004).

The Antarctic Andean Orogen

The orogen of the Antarctic Andes occupies the entire Antarctic Peninsula southward to the Walgreen Coast. It formed mainly in three stages: (1) Late Jurassic through Early Cretaceous (150–140 Ma), (2) Mid-Cretaceous (c. 105 Ma), and (3) Tertiary (c. 50 Ma to recent), and it is partly still active (e.g., Birkenmajer 1994; Vaughan and Storey 1997).

Thus, it represents the youngest growth zone of the continent. The Antarctic Andes are a typical subduction orogen, like the South American Andes, with extensive orogenic magmatism in the form of granitic plutonism and volcanism. In detail, the deformation and metamorphism is very complicated because it is polyphase. Folding and thrust tectonics are reported mainly from the southern peninsula (Palmer Land, Alexander Island) and from the extreme north (Trinity Peninsula and eastern South Shetland Islands). The distribution of types and degrees of related metamorphism(s) is also heterogeneous (A. Wendt, personal communication), including high-pressure metamorphism with blueschists characteristic of subduction complexes (e.g., on Elephant Island) (Trouw et al. 1991).

The Plate-Tectonically Active Parts of Antarctica

The plate-tectonically youngest, and the only plate-tectonically active, part of Antarctica is situated northwest of the Antarctic Peninsula in the South Shetland Islands (from Snow Island in the southwest to Elephant Island in the northeast) and along Bransfield Strait. Northwest of the South Shetland Islands a small section of the Pacific ocean floor, called the Drake Plate, was, and possibly still is, being subducted at the South Shetland Trench beneath the Antarctic Plate. (The Drake Plate is the remnant of the older, but largely subducted, Phoenix Plate.) Related, mainly andesitic, volcanism forms the island arc of the South Shetland Islands. Almost all of these volcanoes are extinct but Penguin Island erupted less than 100 years ago. Parts of the South Shetland Islands (part of Livingston Island and Elephant Island) belong, like the Antarctic Peninsula itself, to earlier stages of the Antarctic Andean Orogen and consist of strongly deformed Jurassic trench sediments.

Bransfield Strait is located southeast of the subduction-related volcanic island arc and forms an active extensional basin accompanied by tholeiitic volcanism, partly submarine, partly as an active island volcano (Deception Island) (Smellie et al. 2002). Bransfield Strait is often regarded as a classic example of a back-arc basin, but recently this has been disputed (Gonzáles-Casado 2000).

Major Fault Systems

The constructive aspect of the geologic development of Antarctica contrasts with the destructive aspect: Antarctica's structure is cut by relatively young extensional faulting. Particularly large and conspicuous fracture zones are as follows:

- The Lambert Graben or Lambert Rift (East Antarctica)
- The West Antarctic Rift System and its major part, the Ross Sea Rift (Pacific sector)
- The graben of Jutulstraumen and Penckmulde (occasionally called the Jutul–Penck Graben [Atlantic] sector)
- The Rennick Graben, the major element of a strike-slip fault system in Victoria and Oates lands

The Lambert Graben developed in the East Antarctic Craton and is filled by sediments of the Permo-Triassic Beacon Supergroup. Faulting began during the early Palaeozoic, reached its peak during the Permian, and continued into the Early Cretaceous (Hofmann 1996). Vostok Subglacial Lake possibly belongs to the same rift system, although it is somewhat offset. The continuation of the Lambert Graben is the Indian Mahanadi Rift southwest of Calcutta in the state of Orissa (Hofmann 1996), filled with sediment of the same type and age as the Lambert Graben. In the reconstruction of the Gondwanan India–Antarctica fit, these graben systems coincide with reconstructions of Archaean to Early Proterozoic elements of Rodinia. This means that the relationship between Antarctica and India during Rodinian and Gondwanan times did not differ substantially.

The Ross Sea Rift is extremely wide (about 1000 km). Its subsidence started during the late Mesozoic (about 140 Ma), reached its main activity in the Early Tertiary (about 40 Ma), and produced an enormous relief at its western shoulder. The difference in altitude between the Transantarctic Mountains and the Ross Sea floor exceeds 14 km. The crustal extension is combined with alkaline, intracontinental volcanism, which is still active at Mount Erebus (3794 m) and Mount Melbourne (2732 m), both located in Victoria Land.

The Jutul–Penck Graben of western Dronning Maud Land probably originated around 140 Ma or a little later (Jacobs and Lisker 1999). The graben marks the boundary of the Grunehogna Craton to the southeast and thus it is following a much older geological structure. A possible continuation of the Jutul–Penck Graben into the still-active East African rift system is under discussion (Graham and Hunter 1991). This is not unlikely because parts of the East African rift system were already active during the Jurassic (Ring and Betzler 1993).

The strike-slip fault system of Victoria and Oates lands trends obliquely to the Ross Sea Rift and is cut by it. It still shows certain activity, demonstrated by earthquakes in 1952, 1974, and 1998, the last two of which were located in the main element of the system, the Rennick Graben. This graben contains down-faulted volcanic rocks of the Ferrar Supergroup and sedimentary rocks of the Beacon Supergroup, which have been spectacularly folded and squeezed onto the graben shoulders. This proves alternating dextral transpression and transtension (with the formation of pull-apart basins), as parts of a complicated strike-slip system (Rossetti et al. 2003). The 1954 earthquake occurred some 120 km to the west at the parallel structure of the Matusevich Glacier. There is an ongoing discussion as to whether this strike-slip fault system constitutes the continuation of the oceanic fracture zones between Australia and Antarctica (e.g., the Tasman Fracture Zone) into the continental crust of Antarctica.

GEORG KLEINSCHMIDT

See also **Antarctic: Definitions and Boundaries; Antarctic Ice Sheet: Definitions and Description; Antarctic Peninsula, Geology of; Beacon Supergroup; Bransfield Strait and South Shetland Islands, Geology of; Deception Island; Drake Passage, Opening of; East Antarctic Shield; Ferrar Supergroup; Gondwana; Islands of the Scotia Ridge, Geology of; Lake Vostok; Marie Byrd Land, Geology of; McMurdo Volcanic Group; Plate Tectonics; Rodinia; Shackleton Range; South Shetland Islands; Transantarctic Mountains, Geology of; Victoria Land, Geology of; Volcanoes; Weddell Sea Region, Plate Tectonic Evolution of; West Antarctic Rift System**

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GEOMAGNETIC FIELD

The Earth's magnetic field—the geomagnetic field—is produced mainly by an internal dynamo source but extends many Earth radii into space. The field is dipolar but the positions of the magnetic poles do not coincide with the geographic poles. Furthermore, the intensity and direction of the field vary with time. In addition to the dynamo source, the field measured at the surface includes contributions due to magnetic sources and electric currents in the Earth's crust, and external sources arising from currents in the ionized part of the atmosphere (the ionosphere) and charged particles reaching Earth from space. Knowledge of the geomagnetic field has advanced greatly during the spaceflight era but is still far from complete.

Discovery and Measurement of the Geomagnetic Field

The nature of the geomagnetic field was first clearly described in 1600 by William Gilbert, court physician to Queen Elizabeth I of England. In what is often regarded as the first true work of modern science, Gilbert used a series of experiments to establish that the Earth is magnetized and possesses magnetic poles. The total strength of this field is around 0.066 milliTesla (mT) near the poles and 0.024 mT near the equator. By comparison, a small bar magnet produces a field on the order of 10 mT.

Although magnetic compasses had probably been used as navigational aids since the twelfth century, the fact that the direction in which a compass points deviates from true (geographic) North by an amount that depends on location was first clearly reported by Christopher Columbus in 1492. This angle of deviation is called the magnetic declination. Knowledge of the declination is important for navigation. The first declination chart of the Earth was developed by Edmund Halley in 1702.

At low and middle latitudes the declination is generally just a few degrees. However, in the polar regions declination can be very large, so the compass needle may point in quite a different direction from poleward. For example, at the Australian Antarctic station Davis, the declination in April 2003 was 78°31′ W, and increasing westerly by about 8′ per year.

Observatories for systematically measuring the geomagnetic field strength and direction were established in the 1840s. Today a global network of magnetic observatories continually monitors the geomagnetic field, contributing data to the World Data Centers for Geomagnetism in Copenhagen, Edinburgh, Kyoto, and Mumbai. Data from these centers are freely accessible and largely online. About eighty observatories around the globe also provide data with 1-minute timing via the International Real-Time Magnetic Observatory network, known as INTERMAGNET. At each of these observatories the geomagnetic field is measured each 5 seconds with a resolution of 0.1 nanoTesla (nT) and an absolute accuracy of 5 nT.

The geomagnetic field is described in terms of its total intensity F and the horizontal intensity H, both measured in nT, the inclination or dip angle I (the angle between the horizontal and the total field direction, in degrees), and the declination D, in degrees. It is also common to describe the field in terms of its intensity in the true north, east, and vertical directions (called X, Y, Z), all measured in nT.

The strength and direction of the geomagnetic field vary over periods from millions of years to fractions of a second. In general, variations with periods longer than about a day are of internal origin. The short-period variations of external origin are a thousand to a million times smaller in amplitude than the main internal field. The magnetic field produced by common objects such as a belt buckle or screwdriver will be of intensity comparable to these rapid variations. Thus, magnetic observatories are constructed from nonmagnetic materials and need to be located a good distance away from sources of electrical or magnetic noise. Two types of instruments are usually used to measure the geomagnetic field. Absolute instruments measure the components of the main background field (F, H, I, and D) in terms of basic physical units. In addition, variometers measure the field's variation from the undisturbed state. Some magnetometers combine both functions with GPS-synchronized digital sampling.

The Dipolar Nature of the Field

A mathematical description of the geomagnetic field was first provided by Carl Gauss in 1839. He recognized that the internal source of the main magnetic field could be represented by a small tilted bar magnet at the geodetic center of the Earth. The resultant field is dipolar and the dipole axis is tilted by about 11° with respect to the Earth's geographic rotation axis. Such a dipole accounts for about 80% of the geomagnetic field at the surface. Gauss also calculated the positions where the best-fitting dipole axis cuts the Earth's surface. These locations are the geomagnetic poles. Vostok Station in Antarctica is located near the South Geomagnetic Pole. Strictly speaking, this is a north pole, because it attracts the south pole of magnets (such as compass needles).

The positions of the actual magnetic poles (or dip poles), where a compass needle stands vertically, depend on local effects in the crust and do not coincide with the geomagnetic poles. The resultant nondipole field accounts for 10%–25% of the field measured at the surface. The dip-pole locations are not readily calculated and therefore measuring their locations was an important goal for early explorers.

The position of the North Magnetic (dip) Pole was discovered by James Clark Ross on June 1, 1831, at 70°05′ N, 96°46′ W. The South Magnetic Pole was first approached in an epic man-hauled sledge journey by T. W. Edgeworth David, Douglas Mawson, and Alistair Mackay, from Ernest Shackleton's British Antarctic Expedition, on January 16, 1909. At that time the pole was located at 71°36′ S, 152°0′ E, over 190 miles (300 km) into the interior of the Antarctic plateau.

In December 2000 the magnetic dip pole was relocated (Barton 2002) by the ship *Sir Hubert Wilkins* at 64°40′ S, 138°01′ E, about 150 miles (240 km) offshore from the French base Dumont D'Urville. It is estimated that since 1841 the South Magnetic Pole has drifted 1300 km, at an average speed of 8.2 km/yr. It is currently drifting northwest at around 4 km/yr. This type of slow field change is called secular variation. For this reason magnetic charts need to be updated periodically. For example, the declination at London, England changed gradually from 11.5° E in 1576 to 24° W in 1823, and is now about 6° W.

Internal Source of the Geomagnetic Field: Dynamo Theory

Magnetic fields are produced by the motion of charges, such as electrons moving in a wire. In the case of the Earth this occurs in the outer core. The continents and ocean floors form the crust of the Earth. Seismic observations show that the underlying mantle extends to about 1800 miles (2900 km) in depth, below which lies the outer core. This encloses the inner core, another 1375 miles (2200 km) further down and about 810 miles (1300 km) in radius. The outer core comprises mostly liquid iron, about 4% nickel and 10% lighter elements, while the inner core is denser and of solid metal. The inner core is produced by solidification of outer-core material as the Earth cools, and is gradually growing in size.

Conditions in the inner core are extreme. The density is about four times that of the crust, and the temperature is similar to that at the surface of the Sun, around 6400°C. The heat in the core remains from when the Earth was formed, and is also provided by radioactive decay processes. Liquid iron deep in the outer core is heated and rises upward toward the mantle, where it cools and then sinks. This convection process is similar to the circulation of water in a saucepan heated on a stovetop. The resultant loss of heat from the deep outer core also causes heavier elements to solidify at the boundary between the inner and outer core. This releases latent heat, further contributing to turbulent convection in the outer core.

The inner part of the outer core rotates faster than the outer part. The linear rotation speed of fluid rising through the outer core under convection is slower than the linear rotation speed higher up. The rising fluid thus imposes drag in the larger radius part of the outer core. The resultant differential rotation of the conducting fluid produces a self-excited dynamo, generating an electric current and hence the main dipole field. Nondipole regional anomalies probably arise from eddy circulations in the outer core.

Secular Variation

The geomagnetic field is locked to fluid motions of the core. This means that the secular variation is directly related to processes in the dynamo source, and that understanding of the Earth's interior requires detailed knowledge of the secular variation (e.g., Jackson et al. 2000). Several factors may influence the dynamo process, including changes in the Earth's rotation rate and changes in the mass distribution at the Earth's surface due to ice ages or a major asteroid impact. It has been suggested that the secular variation exhibits periods of roughly 8000 and 400 years (Yukutake 1973), although many factors may influence the data and analysis (Barton 1983). On a time scale of millions of years, movement of the magnetic poles appears to be linked with large-scale tectonic processes such as continental drift.

The strength of the main geomagnetic field is described by the Earth's dipole moment, in units of Amp m^2. This has steadily decreased by about 20% over the last 400 years (Barton 1989). The significance of this is not clear. However, it is well established that the geomagnetic field completely reverses direction from time to time. The last such reversal was about 780,000 years ago, referred to as the Brunhes-Matuyama reversal. Short-duration decreases in the dipole moment have occurred more recently.

Evidence of magnetic reversals occurs in the pattern of alternating magnetic polarities seen in solidified lava along the sea floor. These patterns arise from the cooling of hot magma as the continental plates spread out away from midocean ridges. The cooling magma carries with it magnetization characteristic of the ambient magnetic field. Since the sea floor spreads at a more or less constant rate, this pattern provides a timeline of the field polarity. The discovery of these magnetic patterns was invaluable to the theory of plate tectonics.

Reversals occurred on average each 750,000 years 50 Ma, but by 10 Ma this rate had decreased to about 200,000 years. The geomagnetic field appears to have no long-term preference for either polarity.

Occasionally there may be a sudden (on the order of a year) change in the general trend of secular variation. Such changes are called magnetic jerks. Recent jerks occurred in 1925, 1969, 1978, and 1992. They are unpredictable and their cause is unknown.

The Crustal Field

The contribution to the observable geomagnetic field arising from magnetic materials in the Earth's crust is often called the anomaly field. This field varies on all spatial scales and is mapped with ground-based, marine, aeromagnetic, and satellite surveys. Such activity has two practical applications. First, magnetic charts including crustal contributions are necessary for precise navigation. Second, magnetic surveys delineating the crustal field provide vital information to the geophysical exploration community that is concerned with locating and exploiting mineral deposits. Surveys of this nature can be contaminated by short-period field variations of external origin.

High-precision measurements of the geomagnetic field from spacecraft missions such as Oersted and Champ provide detailed data on the crustal field, and allow the surface-level field to be extrapolated to the core–mantle boundary. This provides important information to mathematical and laboratory-based models that try to mimic and predict the complex turbulent convection processes in the core that drive the dynamo field. The most sophisticated of these models are able to simulate geomagnetic field reversals, although it is not possible to say with what accuracy.

Models of the Geomagnetic Field

While it is relatively easy to describe the geomagnetic field in terms of a centered dipole, this is a poor approximation to the actual field. A significant improvement is gained by using an eccentric axis dipole, based on a tilted dipole source displaced about 325 miles (520 km) from the Earth's center, toward the Philippines.

The most widely used model of the geomagnetic field is the International Geomagnetic Reference Field (IGRF). This is based on a multipole expansion using a series of mathematical functions, spherical harmonics that characterize the physical properties of the observed field. The IGRF includes data on the secular variation and crustal contributions obtained from ground-based and spacecraft observations, and is updated at five yearly epochs. The location of the IGRF magnetic pole is very close to the actual measured dip pole.

Since the distribution of magnetic observatories is concentrated in the industrialized countries, and because of the locations of the magnetic poles, observations from the polar regions are particularly important to such geomagnetic field models. Historical data are also vital for retrospectively defining the past field.

The Corrected Geomagnetic coordinate system (CGM) is a derivation of the IGRF but more accurately represents the field line paths following by moving charged particles. The joint French/Italian Antarctic station, Concordia (also called Dome C), which opened in December 1997, is located at 75°17′ S, 123°63′ E, 3220 m above sea level, 950 km from the coast, and very near the CGM pole. Part of the reason for establishing a station at this challenging location is that at this great height above the continental crust, magnetic measurements are unaffected by contributions from crustal anomalies. In addition to being near the CGM pole, this makes Concordia an ideal location to study geomagnetism.

Because of the offset of the dipole field, the surface magnetic field strength reaches a minimum in the Atlantic Ocean just off the southeast coast of Brazil. This is called the South Atlantic Magnetic Anomaly (SAA). Since the motion of charged particles arriving from space is usually directed along magnetic field lines, such particles reach their lowest altitudes near the SAA. This can result in high radiation doses that may affect humans and damage spacecraft in near-Earth orbits that traverse the SAA. Such spacecraft suffer the greatest number of radiation-induced operational anomalies near the SAA, and the International Space Station incorporates extra shielding to protect the crew against the enhanced radiation experienced there.

External Contributions to the Field

Measurements from magnetic observatories show systematic seasonal and diurnal variations that are due to motions of the upper atmosphere driven by the variation in solar radiation with time and latitude and the gravitational pull of the sun and moon. This results in winds and tidal forces that drive motions of charged particles in the ionosphere, usually around 65 miles (105 km) in altitude. The resultant electric currents cause a quiet day variation in the ground-level magnetic field.

These ionospheric currents also give rise to currents within the conducting layers of the Earth. The precise magnitude and direction of these currents depends on the electrical conductivity profile. The quiet-time diurnal ionospheric currents thus form a convenient source for mapping the conductivity profile of the Earth.

In the polar regions there is an additional ionospheric current system that produces larger magnetic variations on time scales of an hour or so. Called the auroral electrojet, this is an intense westward electric current in the ionosphere that is associated with active auroral displays. It produces strong magnetic variations. The polar geomagnetic field lines stretch from the Earth's surface a long distance into space—typically 10 Earth radii on the day side and much further on the night side. The enclosed volume is called the magnetosphere and contains significant populations of charged particles. The geomagnetic field lines provide a conduit to the ionosphere for these particles. The most energetic such particles are cosmic rays, mostly protons accelerated from the Sun and other stars. There is good reason, therefore, to locate cosmic ray observatories in Antarctica. One such observatory is at Australia's Mawson station.

A large population of energetic charged particles orbits the Earth in the Van Allen radiation belts. The motion of these particles Earthward produces field-aligned currents that drive the auroral electrojet. The existence of these field-aligned currents was first proposed by the Norwegian scientist Kristian Olaf Birkeland in 1908, and therefore they are often called Birkeland currents. In a series of remarkable experiments, Birkeland constructed a terrella—a small magnetized sphere representing a model of the Earth in space—and created artificial auroras around its magnetic poles using electron beams. He thus demonstrated that auroras are caused by electrically charged particles traveling Earthward along magnetic-field lines and energizing gas molecules in the polar atmosphere. He also reasoned that these energetic electrons affect the geomagnetic field, thus causing polar magnetic storms. Norway honors Birkeland on its 200-kroner banknote.

The existence of Birkeland currents was only proven in 1974 by observations from the Triad spacecraft, which was carrying suitably sensitive magnetometers over the polar ionosphere. These currents have important consequences apart from characterizing the location of auroras. Spacecraft in low-Earth orbit use magnetometers for attitude control, by determining their orientation with respect to the main geomagnetic field. However, as such a spacecraft passes over the polar regions, the magnetic fields produced by the Birkeland currents may be sufficient to affect the spacecraft's altitude-control system. Magnetometer data from networks of communications satellites can be used to map the precise location and size of the Birkeland current systems.

The South Magnetic Pole is located a considerable distance from the geographic South Pole. This has an interesting effect. During summer the polar ionosphere is continually sunlit. This produces enhanced ionization at relatively low magnetic latitudes over the Antarctic Peninsula. Ionospheric winds are then able to drive charged particles up the geomagnetic field lines, resulting in an anomalously high particle density on those field lines compared to other longitudes.

Geomagnetic Disturbances

In addition to secular variation, the magnetic poles also move on relatively short time scales. During measurements from *Sir Hubert Wilkins* over December 21–22, 2000, the South Magnetic Pole was initially about 360 km from its expected position, and moving at 17 km/hr. The pole then moved to the predicted position and settled down to a small elliptical path close to the IGRF pole. Such short-period motions are due to external contributions to the geomagnetic field associated with the effect of the solar wind on the magnetosphere, including magnetic storms and ULF pulsations.

During the International Polar Year in 1932 a system was developed to characterize the level of disturbance of the geomagnetic field due to these external effects. This is based on indices describing the level of disturbance each three hours, called K indices. The K indices from typically 12 observatories around the globe are averaged to produce the 3-hourly planetary magnetic activity index, Kp. Today this is the most widely used measure of geomagnetic disturbance.

Magnetic storms produce a variety of effects on terrestrial and space-borne systems. These phenomena are collectively termed space weather. For example, the petroleum industry uses the geomagnetic field to guide directional drilling toward oil reservoirs. Typical accuracies required are 0.1° in direction and 50 nT in total intensity. This requires knowledge of the crustal field, daily variations, and space weather effects such as magnetic storms.

Frederick Menk

See also **Aurora; Auroral Substorm; British Antarctic (*Nimrod*) Expedition (1907–09); Cosmic Rays; David, T. W. Edgeworth; Geospace, Observing from Antarctica; History of Antarctic Science; International Geophysical Year; International Polar Years; Ionosphere; Italy: Antarctic Program; Magnetic Storm; Magnetosphere of Earth; Mawson, Douglas; Plasmasphere; Ross, James Clark; Solar Wind; South Pole; ULF Pulsations; Vostok Station**

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GEOPOLITICS OF THE ANTARCTIC

In considering the nature of Antarctic geopolitics over the past century, four particular dimensions stand out: (1) territorial ambitions, which relate to the quest by states to demonstrate sovereignty over Antarctic lands; (2) spatial considerations, which refer to the crucial impact of how the Antarctic environment affects the aspirations of states; (3) strategic designs, which reflect attempts by governments to exercise calculated objectives in the Antarctic; and (4) resource acquisition, which concerns the greater importance felt by states to secure access to Antarctic natural resources. Taken in combination, these considerations have shaped national geopolitics in the Antarctic, so much so that they pushed an evolutionary trend in state behavior in the region from bilateral rivalry and conflict up until the mid-1950s to the progressive codification since then of peaceful cooperation through a special multilateral regime.

National geopolitical rivalries in the Antarctic aroused controversy over territorial ambitions throughout the last century. Before its discovery in the early nineteenth century, the continent was uninhabited and belonged to no one. No universally accepted treaties or legal principles governed activities in the Antarctic or defined jurisdiction over that continent's territory and resources. Antarctica was considered *terra nullius,* literally no man's land, a frozen ice-covered continent at the bottom of the world. Beginning in the early twentieth century, however, seven governments progressively asserted pie-shaped claims to Antarctica as portions of their own national territory. While these claims to Antarctica persist today, they are not recognized by any government other than that of the claimants themselves. Consequently, these claims carry salient geopolitical implications for the legal status of the continent and its circumpolar waters.

The United Kingdom was the first government to assert a claim to the Antarctic continent. Known officially as the British Antarctic Territory, the United Kingdom's claim was made in 1908 and goes south of 60° S between meridians 20° and 80° W to the South Pole. The area covers some 700,000 square miles on the continent, including "Graham's Land" on the Antarctic Peninsula. The UK claim also encompasses important island groups in the Southern Ocean, namely the South Orkneys, South Shetlands, South Georgia, and the South Sandwich group. In the case of South Georgia, the establishment of a local government and the collection of taxes are made a fundamental part of the claim. While not formally a geographical part of the Antarctic, the Falkland Islands prominently figure to geopolitics in the region. British sovereignty over the islands has been disputed by Argentina since the 1820s. In April 1982 Argentina invaded "Las Malvinas" and other British territories in the South Atlantic (South Georgia and the South Sandwich Islands), igniting war with the UK. By June the British had won the conflict and established control over all the island groups in the region. The UK claim to Antarctica rests mainly upon the exploits of British explorers in the circumpolar seas. Captain James Cook visited these waters in January 1775 and claimed South Georgia in the name of King George III. He also discovered the South Sandwich Islands group. In 1819, William Smith discovered the South Shetland Islands and claimed them for Great Britain. One of the earliest sightings of the Antarctic mainland was made in 1820 by Edward Bransfield, a Royal Navy officer. The South Orkney Islands were claimed in 1821 for the British Crown by George Powell. During 1841–1843, Sir James Clark Ross circumnavigated the continent, charted some 500 miles of coastline along Victoria Land, and discovered Ross Island, as well as the northern edge of the Ross Ice Shelf. In January 1843, Sir Ross landed on Palmer Peninsula and claimed Ross Island and all "contiguous lands" for the British Crown.

British claims to administer legal title in the Antarctic were first set out in a King's Letters Patent of 1908. This royal proclamation formally established the Falkland Islands Dependencies, consisting of the Falkland Islands, South Georgia, the South Orkneys, the South Shetlands, the South Sandwich group, and Graham's Land on the continent. In March 1917 a second Letters Patent was issued to elucidate Great Britain's claim. This decree included all islands and territories between 20° and 50° W situated south of 50° S, as well as all islands and territories between 50° and 80° W situated south of 58° S. When depicted today on a map, the geopolitical implications of the British claim become stark: The UK claim overlaps in substantial part with contending claims of sovereignty made by Chile in 1940 and Argentina in 1945 to the Antarctic Peninsula, an area that possibly contains petroleum, natural gas, and mineral deposits. It bears remembering that not only do the United Kingdom and Argentina share contentious claims over the Antarctic Peninsula, they also dispute the ownership of several sub-Antarctic islands and went to war when Argentina invaded South Georgia and the Falkland Islands in 1982.

New Zealand's claim to Antarctica, known as the Ross Dependency, covers 175,000 square miles and runs south of 60° S between 160° E and 150° W, extending to the South Pole. By an Order-in-Council in 1923, this wedge of Antarctica was entrusted by the United Kingdom to New Zealand. The subsequent legal grounds posited by New Zealand for its claim rest in discoveries by the British explorer Admiral James Clark Ross in 1841, as well as expeditions by Robert Scott and Earnest Shackleton between 1901 and 1909. Further legitimacy for New Zealand's claim supposedly flows from the title originally asserted by Great Britain (Logan 1979).

France claims the smallest portion of the continent, a 150,000-square-mile wedge called Terre Adélie. The

French claim runs between 136° and 142° E, extending to the South Pole. The French sector in fact bisects the Australian claim. The legal ground for the French claim is discovery, particularly the voyage of Dumont d'Urville in 1840. While considerable weight is given to d'Urville's discoveries in the region, he never set foot on the continent. The French exercise uncontested sovereignty over some islands in the Antarctic Ocean, namely Kerguelen, Crozet, Amsterdam, and St. Paul. These islands, along with the Adelie Land on the continent, were administered by the Governor General of Madagascar until 1955. Since then, the French Southern and Antarctic Territories have been administered by the Terres Australes et Antarctiques de France (TAAF) in Reunion, as a part of the Ministre d'Outre Mers.

Australia has the largest claim to the continent. With an area of 2.4 million square miles, the Australian Antarctic Territory covers the region south of 60° S between 45° and 160° E, running to the South Pole, except for the wedge claimed by France. Australia in effect claims two large sectors on the continent. Australia states two main legal grounds in support of its Antarctic claims. The first consists of the acts of discovery made by British and Australian explorers, especially that of Captain Cook's circumpolar voyage in 1770–1775, which is buttressed by the expedition in 1910–1911 of Sir Douglas Mawson. The second is that Australian nationals have established a continuous occupation in Antarctica, characterized by administrative acts and civil control. Australia's sectors were originally part of the British claim made in 1908. Australia requested that the United Kingdom declare a sovereign claim to the Antarctic mainland on its behalf. This was done in 1933 by a British Order-in-Council that transferred title to Australia and entered into effect in 1936. Australia contends that, in legal terms, its claim rests on effective occupation of the continent since then (Morgan 1996).

Norway claims a part of Antarctica known as Dronning Maud Land. The Norwegian claim includes the Antarctic mainland, running from the Falkland Islands Dependencies in the west at 20° W to the Australian Antarctic Territory in the east at 45° E. Covering an area of 1.2 million square miles, the Norwegian claim was declared by royal decree in 1939. The immediate catalyst for Norway's decree stemmed from geopolitical concerns about reports that Nazi Germany intended to stake a claim in the Antarctic. The legal basis for Norway's claim to title, however, rests on "geographical work done," ostensibly during the expedition by Roald Amundsen during 1910–1912, which had no relationship to Dronning Maud Land. Norway's claim differs from other claims to the Antarctic in that it relies less on discovery than on actual occupation and historical use of the circumpolar seas by national whaling fleets. It is also distinguished from other claims by its having neither a defined northern nor a defined southern terminus. Paradoxically, Amundsen, the first man to reach the South Pole, had in fact laid claim to the polar plateau in December 1911 for King Haakon VII of Norway. That precise basis was never legally articulated or formally acknowledged by the Norwegian Government. Norway's decision not to allow its claim to terminate at the South Pole was prompted by a pragmatic geopolitical consideration: if this Antarctic claim were acknowledged, it would imply formal substantiation of Norway's validation of using sectors as permissible means for demarcating polar territory. Such a circumstance would undercut Norway's legal position for claims it made to territory in the Arctic, which were originally contested by the Soviet Union (now Russia). In the Arctic, Russia continues to assert a sector claim to Spitsburgen in the Svalbard archipelago such that it geographically disadvantages a Norwegian claim to the same territory. To admit the validity of using the sector device anywhere would be tantamount to admitting the validity of the contentious Soviet (Russian) claim. Consequently, Norway's proclamation of sovereignty in the Antarctic was judiciously calculated to avoid asserting a sector-shaped claim there in order to safeguard its geostrategic and legal interests in the Arctic.

The claim by Chile to its "Territorio Chileno Antartico" extends from 53° to 90° W, terminating at the South Pole. While Chile has not officially declared the endpoint for its northern baseline, cartographers generally place it at 60° S, an action that has not provoked any formal protest by the Chilean Government. One wonders why this has been the case, since Chile's claim was made prior to the Antarctic Treaty in 1959 and would naturally converge at the South Pole. Chile's claim covers some 500,000 square miles. Prior to 1940, Chile expressed scant interest in the south polar region. It was then, however, that President Aquirre Cerda issued an executive decree that the Chilean Antarctic was comprised "by all lands, islands, islets, reefs, pack-ice, etc. known and to be discovered, and their respective territorial sea, lying within the limit" of the above sector coordinates. It is significant to realize that Chile's claim overlaps those of Argentina and the United Kingdom, both of whom could present evidence of prior historical assertions to title. It was not until 1947 that Chile established a permanent base in the South Shetlands, which provides the earliest demonstrable support for what might be considered Chile's "effective occupation" in the Antarctic.

The legal foundation for Chile's claim substantially reflects that of Argentina. Contemporary title is said to have been transferred to Chile by the 1493 Papal *Inter Caetera,* as supplemented by the 1494 Treaty of Tordesillas between Spain and Portugal. Chile alleges that it also inherited lawful claim to title to Antarctic territory upon its independence from Spain in 1810 *(uti possidetis)*. Chile, like Argentina, contends that privileged legal positions stem from its geologic contiguity and geographic proximity to the Antarctic. Chile additionally contends that effective occupation of the continent has been demonstrated, although only since 1947. It was then that the Chilean government began undertaking special administrative deeds intended to shore up the lawfulness of its sovereignty assertions to the continent. It is important to underscore the geopolitical implications that flow from Chile's assertion to title in the Antarctic. For one, its claim to territory on the Antarctic Peninsula overlaps those of the United Kingdom and Argentina. For another, Chile's historical relationship to Argentina since 1880 at times has been hostile and tense. Third, Chile is the sole claimant whose initial assertion in 1940 included sovereign rights to a territorial sea, although it has not openly exercised such offshore jurisdiction since then (Child 1985; Pinochet de la Barra 1955).

The last claim to title in the Antarctic was made by Argentina in the mid-1940s. This claim, known as "Antartida Argentina," extends south of 60° S, from 25° to 74° W, and dovetails at the South Pole. Argentina's claim encompasses some 550,000 square miles and includes territory in the Antarctic Peninsula, as well as several islands, among them the South Orkneys, the South Shetlands, South Georgia, and the South Sandwich group.

Argentina's Antarctic claim was initially asserted by Juan Peron and first appeared on special maps published by the government in December 1946. Argentina alleges that four legal pillars support its south polar claims. First, Argentina contends that it has performed since February 1904 uninterrupted maintenance of the Laurie Island weather station in the South Orkneys, an action that purportedly demonstrates adequate effective occupation to meet the requirements for territorial sovereignty in the entire region. Certainly Argentina has sought to underline its claims in the Antarctic by periodically performing symbolic acts intended to validate administration of its polar territory. Such acts include depositing special plaques, designating postmasters, coroners, and local magistrates for the region, issuing special postage stamps commemorating Argentina's claimed territories, arranging to have children born there, and even declaring a national "Antarctic" holiday (Fraga 1979).

A second pillar of legal support is Argentina's contention that, under the doctrine of *uti possidetis juris,* valid lawful title to Antarctic territories was transferred to Argentina when it separated from Spain. Like Chile, Argentina argues that historical support for this legal contention flows from the Papal Bull *Inter Caetera* of 1493 and the Treaty of Tordesillas of 1494. Under these arrangements, Pope Alexander VI divided up the Western Hemisphere between Spain and Portugal. Spain was given the entire world west of the 46th meridian, extending from pole to pole. Thus, Argentina maintains that it succeeded to this legal title to Antarctic lands upon its independence from Spain in 1816. Modern international law, however, attaches no legal credibility to papal edicts issued 500 years ago as justification for making a claim of sovereign title to territory.

Propinquity, or geographical proximity, supplies a third pillar for Argentina's claims. The geographical fact that Argentina (along with Chile) is nearest to Antarctica supposedly confers to that state a special and unique right to claim territory on the continent. A fourth pillar used by Argentina to support its claims is geological affinity with the Antarctic region. This line of reasoning argues that the Andes Mountains form a continuous geomorphological chain stretching from South America, under the Southern Ocean, to the Antarctic continent. As a consequence, Argentina should be given preferential priority to claims made to geologically attached areas. In sum, Argentina's claims appear to be couched in legal supposition, but in fact are grounded in geopolitical nuance (Joyner and Ewing 1991).

Geopolitical spatial considerations impact heavily on the lawfulness of claims made to Antarctica. That is, environmental conditions tend to confuse the lawful acquisition of sovereign rights to Antarctica. First, there is the geophysical fact that a mantle of ice nearly 3 miles thick in some places overlays the continent. This condition makes Antarctica's environment extraordinarily harsh and hazardous compared to other continents. The overwhelming presence of ice, aggravated by persistent severe weather conditions, impairs the possibility of establishing effective occupation through permanent settlement on the continent, the critical requirement in modern international law for confirming sovereignty over a territory. Second, the legal status of claims in the Antarctic is susceptible to doubt on account of the inability of claimant governments to perfect their claims to title. Discovery of lands is not sufficient to claim sovereign title to territory. Modern international law requires that a claimant secure physical possession and maintain continuous performance of governing acts to indicate the legitimate authority of the claimant state over that territory. Title must be perfected through effective occupation within an undefined, but "reasonable time." Third, claimant governments have not been able to demonstrate through permanent settlement authoritative political, economic, and civil ties to the continent; consequently, they have not been able to generate international recognition that their claims to title are legitimate. In sum, it is not possible to affirm in a compelling manner that permanent settlement giving rise to effective occupation of the continent has been demonstrated authoritatively by any claimant. Colonists from states do not live permanently in the Antarctic; scientists and logistical personnel from many nationalities work there temporarily (Joyner 1991).

Assertion to title in Antarctica highlights the geopolitical notion of sector claims. As officially depicted on maps, claimed areas to the Antarctic continent resemble pie slices that are demarcated by two meridian lines that converge in an apex at the South Pole. Five of the seven claims assert the same baseline of latitude, namely 60° S. The United Kingdom's claim is earmarked by a step-shaped baseline, with a lower rung fixed at latitude 58° S and the upper edge set at 50° S. Norway's claim has designated neither a latitudinal baseline, nor official government acknowledgment that the claim formally terminates at the South Pole. The so-called sector "principle" that purportedly supports these wedge-shaped claims originated in a statement in the Canadian Senate on February 20, 1907 when Senator N. P. Poirier recommended that Canada officially declare possession of the lands and islands lying between the extremes of its northern coast and the North Pole. While the Canadian government did not immediately take up Poirier's suggestion for the Arctic, the British government did so in the Antarctic through its Letters Patent of March 28, 1917. Yet the fatal flaw with the sector device is the inherent contravention of established practical legal norms. What legal basis exists for their extension? Sector claims advanced in the south polar region allegedly rest on specific points where discovery occurred, as well as on combinations of historical appropriation, geographical propinquity, and alleged acts of administration. Yet three of the seven claims—those by Argentina, Chile, and the United Kingdom—overlap substantially, thereby subjecting the entire Antarctica Peninsula and the Weddell Sea area to contradictory zones of jurisdiction. This situation demonstrates the specious validity of the sector claim as a legitimate device of delimitation, largely because of its geopolitical qualities and mechanistic attributes. In sum, resort to a sector claim may be considered a convenient geopolitical device employed by some governments to rationalize their national policy positions in the polar regions, but such a device is not considered a legitimate construct under modern international law. The status of claims made to the continent presents legal implications for any claims made to territorial rights in circumpolar Antarctic seas. For one, Antarctica is a continent without any internationally recognized state. The logical assumption is that because no recognized state exists on the continent, no zones of jurisdiction may be extended seaward from Antarctica. If territoriality cannot be projected from the continent to include territorial waters or other offshore zones, the logical conclusion follows that high seas extend up to the edge of the continental land or ice shelves. In this regard, it is noteworthy that no claimant government has suggested it claims within its wedge all waters northward from the continent's edge to 60° S, although Chile in its 1940 decree intimated such a claim to territorial waters, but never acted on that presumption (Joyner 1991).

Another important realization is that establishment of offshore jurisdictional zones first requires designation of a baseline from which the breadth of these zones can be measured. Unlike other continents, Antarctica is covered by an immense ice sheet that feeds into huge ice shelves along the margins. These ice shelves are either floating or locally grounded. Since the ice sheet is constantly moving seaward, massive pieces frequently calve off the continent into the ocean. Thus the Antarctic "shoreline" is constantly changing. In addition, Antarctica is surrounded by seasonal accumulations of fast ice and pack ice that can grow out in the winter to cover 7.3 million square miles of the Southern Ocean. These natural occurrences severely complicate the ability to delimit according to international legal techniques regarding standard baselines for setting offshore jurisdiction. This notwithstanding, Australia has officially declared that it controls a 200-mile exclusive economic zone offshore of its Antarctic territory. Moreover, in November 2004, Australia submitted official documents to the UN Commission on the Limits of the Continental Shelf that indicated that it claimed special rights to the continental shelf protruding from Antarctica into the circumpolar seas. Interestingly, it is the only claimant state to do this.

Geopolitical strategic designs figure heavily into some states' rationales for an Antarctic presence. This is especially true for Latin American attitudes, especially in Argentina and Chile, toward the polar south. Latin American geopolitical thought toward Antarctica views present policy in terms of future expectations. Argentine geopolitical thinkers view their country as a "Tri-Continental nation." Sovereignty is viewed as encompassing territory (1) on the

South American continent; (2) in "Insular Argentina," consisting of several island groups (namely, the Malvinas/Falklands, South Orkneys, South Sandwich Islands, and South Georgia); and (3) in Antarctic Argentina. All of these are linked together by the "Argentine Sea," that is, waters in the South Atlantic and Southern Ocean. For Argentina, the key to national greatness lies in the ability to resist external challenges to this vital geopolitical space through control of these territories and vital circumpolar waterways. Thus, Argentina's post–World War II policy toward Antarctica was highlighted by a geopolitical nationalism that perceived threatening competitors, namely Chile and the United Kingdom, vying for Argentina's critical space in the polar south (Fraga 1979). More recently, however, the internationalization of the circumpolar region under the Antarctic Treaty System has moderated the intensity of Argentina's geopolitical nationalism in favor of multilateral cooperation. Argentine policy now accepts creation of an Antarctic "zone of peace," the expansion of scientific exchange and collaboration, the exercise of inspection rights, and regular participation in annual Antarctic Treaty Consultative Party meetings. In 2004, the Antarctic Treaty Secretariat was opened in Buenos Aires, an important symbolic achievement for Argentina's role in the Antarctic Treaty Consultative Party group. Even so, Argentina has not abandoned its core geopolitical idea of maintaining national claims to territories in its Tri-Continental area (Child 1988; Dodds 1997; Joyner and Ewing 1991).

Chile's geopolitical approach to Antarctica is guided by geographical proximity. As the state closest to Antarctica, Chile has geopolitical perceptions that share the concept of tri-continentalism. For Chile, there are its territory on the South American mainland, certain island territories in circumpolar waters, and the Antarctic continental sector, all of which are united by "the Chilean Sea." In this regard, Chile pursues twin goals of maintaining national territorial sovereignty and articulating maritime rights in the Antarctic, not only historically in negotiations with Argentina and the United Kingdom, but also in legal proclamations and vigorous base-building in the region. Chilean geopolitical thinkers emphasize Chilean sovereignty throughout its tri-continental space. In addition, Chilean geopolitical thought places great emphasis on maritime rights, especially the notion that Chile is the guardian of three geostrategically salient southern passages: the Beagle Channel, the Strait of Magellan, and the Drake Passage. Since entry into force of the Antarctic Treaty in 1961, Chile has pursued a two-pronged strategy toward the Antarctic. On the one hand, Chile actively participates in and supports Antarctic Treaty institutions, but on the other hand, Chile pushes policies that seem to reinforce Chilean claims and place Chilean nationals as leaders in both scientific bodies and political institutions in the Antarctic Treaty System (Child 1988; Dodds 1997).

The Cold War ushered more geopolitics into Antarctic affairs. By the late 1940s, concern was mounting among US policymakers over the Soviet Union's emerging interest in Antarctica. Prompted by events in Eastern Europe, the United States became wary about Soviet intentions—not only their desire to exert more influence internationally, but also the possibility that Moscow might view Antarctica as geostrategically important. US policy embraced the objective of dissuading the Soviet Union from attempting to establish a territorial claim on the continent. In June 1948, US policy toward the Antarctic was officially set out in PPS-31, a strategic plan by the Policy Planning Staff of the Joint Chiefs of Staff. This paper acknowledged that while securing a claim to Antarctica was not critical to US interests, denying the Soviets access to the continent was. The United States was particularly concerned that the Soviet Union might set up bases in the unclaimed portion of the continent, where the United States had established in the 1930s and 1940s a firm legal basis for its own claim.

During the Korean War, the anti-Soviet theme became fixed in US Antarctic policy. Both states increasingly turned their attention to both poles, as serious concern surfaced that East–West rivalry, with its inherent tensions, might generate Cold War politics in Antarctica. Such a development could complicate geopolitical problems over sovereignty and, more ominously, possibly precipitate an arms race, leading to testing and implantation of nuclear weapons on the Cold Continent. It would be prudent to avoid such geopolitical circumstances.

By the mid-1950s, US policy had softened as the opportunity for Soviet involvement in Antarctic affairs was opened by preparations for the International Geophysical Year (IGY). This occasion marked the Soviets' first international involvement in Antarctic affairs. Still, Australia remained sensitive about Soviet geopolitical intentions with the establishment in 1956 of Mirnyy Station on the coast of its sector claim and the concern that it might become a submarine facility that threatened shipping lanes in the Indian Ocean. Even so, Soviet participation in the IGY from July 1957 through December 1958 demonstrated the Soviet commitment to scientific interests and opportunities for cooperative research. The launch of Sputnik on October 4, 1957 supplied the strongest motivation for the United States to seek post-IGY conference negotiations. Other important geopolitical developments occurring during the IGY included the Soviets' establishing major scientific stations in each of the claimed sectors and the United States' construction of its Amundsen–Scott station at the South Pole, the very point where all the claimed sectors (except for Norway's) converge.

The highly productive multilateral scientific cooperation during the 1957/1958 IGY prompted participating governments to believe that such cooperation should be preserved diplomatically in a legally binding arrangement. At the invitation of the United States, delegates from the twelve participating states in the IGY (the seven claimant states, plus five nonclaimant states active in Antarctic affairs, the United States, the Soviet Union, Japan, Belgium, and South Africa) convened periodically from May 1958 through November 1958 in meetings intended to negotiate a treaty for the Antarctic. This agreement was completed on December 1, 1959. The Soviets contributed two very critical ingredients that impacted these negotiations. First, they argued for a system of unanimity voting, which eventually became adopted as a consensus arrangement; second, they suggested that the Antarctic Convergence be made the boundary for the treaty's northernmost jurisdictional reach. This biologically based suggestion was overridden in favor of a Chilean proposal to use the 60° S mark as a more convenient geopolitical mark. Important for Antarctic geopolitics, the Soviets accepted a treaty provision for unannounced, onsite, or aerial inspections for violations by one party of another party's polar stations, ships, or personnel. In the spirit of international cooperation, the Soviet Union also accepted the insertion of provisions that demilitarized and denuclearized the treaty area and preserved the region for peaceful uses only (i.e., mainly for science). Finally, the Soviets accepted Article IV, which provides for claimant states to retain their claims, while at the same time permitting nonclaimant states to persist in not recognizing those claims. While often criticized for being legally ambiguous, Article IV effectively shelved any intentions the Soviets (or the Americans) harbored for asserting national claims to the continent throughout the life of the Antarctic Treaty (Joyner 1989).

Geopolitical concerns implicit in states' claims to sovereignty on the continent were alleviated by successful negotiation of the Antarctic Treaty in 1959. The key to reaching a desirable outcome was Article IV in the treaty. This provision is the "flexi-glue" that allows the Treaty to function, as it provides a political context in which all parties can cooperate in Antarctic affairs, while at the same time allowing governments to agree to disagree on where, when, how, and if sovereignty can be lawfully acquired by states in the polar south. Through Article IV, disagreement over the legitimate status of the claims was negotiated into legal limbo among Antarctic Treaty parties. It is essential to understand that all the claimant states were original parties to the Antarctic Treaty and were therefore included in this cooperative relationship. Likewise, the five nonclaimant IGY participants were original parties. For all these governments, and the thirty-three other governments that became parties thereafter, the legal legerdemain of Article IV sets aside disputes over sovereignty for the sake of international cooperation, at least for the duration of the Treaty (Joyner 1991, 1998).

Concern over the geopolitics of resource acquisition, which could lead to environmental degradation, has dominated the Antarctic Treaty parties' attention since the agreement entered into force in 1961. In 1964, at the behest of SCAR, the parties adopted special measures to conserve Antarctic flora and fauna on the continent (see Agreed Measures for the Conservation of Antarctic Flora and Fauna). These rules restricted access by nationals of treaty parties to certain places on the continent. In 1972, when reports surfaced that the Soviets might resume seal hunting in the region, a special convention was negotiated to protect Antarctic seals. Increased harvesting of krill and fish by the Soviets and Japanese in the 1970s prompted the treaty parties in 1980 to create a special regime to protect and conserve marine resources living in the Southern Ocean. This regime, which extends beyond the treaty area northward to the Antarctic Convergence (Antarctic Polar Front) around 55° S, oversees and regulates the harvesting of Antarctic marine life. The commission established by the living marine resource conservation regime provides the principal forum for setting catch ceilings and establishing no-fishing zones, not only for krill but also for finfish. This body also serves as the principal multilateral forum for monitoring unreported, unregulated, and illegal fishing in the Southern Ocean. It does not attempt to regulate whaling, however, since that responsibility falls to another multilateral forum, the International Whaling Commission (Joyner 1998; Rothwell 1996).

International geopolitics affecting the south polar area intensified during the 1980s. During this decade, the Antarctic Treaty parties negotiated a special regime to regulate the exploration for and exploitation of minerals in and around Antarctica, if ever those possibilities should occur. These special negotiations sparked international debate and condemnation in the UN General Assembly about the ownership of Antarctic mineral rights. Led by Malaysia's objections, developing countries asserted that these special negotiations amounted to a grab for Antarctic mineral resources by rich, developed states. While the treaty parties produced in 1988 a draft text for an Antarctic mineral treaty, Australia, France, and New Zealand declined to support the agreement, thereby precluding its possible ratification (Joyner 1996). The Antarctic Treaty parties then reversed course in 1990 to negotiate a protocol to the 1959 agreement that provides comprehensive environmental protection in the region (the Protocol on Environmental Protection to the Antarctic Treaty). This environmental protection protocol was completed in 1991 and entered into force in 1998. Importantly, it prohibits mineral exploitation and drilling activities in the Antarctic for at least 55 years, and goes far to strengthen resource conservation and environmental protection regulations throughout the Antarctic (Joyner 1998). In 2005, the treaty parties adopted a special annex to the protocol that elaborates a liability regime for persons who do damage to the Antarctic environment.

National geopolitics throughout the twentieth century furnished great incentives for developing international legal rules and acceptable policies for cooperative interstate activities in the Antarctic. The 1959 Antarctic Treaty and its constellation of associated agreements now furnish the principal regulatory regime for institutionalizing legal governance and international oversight of activities in the Antarctic. At the same time, they diminish concern for national geopolitical ambitions by the states most interested in the Antarctic. But if the past is prologue, the negotiation of new legal instruments will be necessary to deal with new geopolitical concerns and the onset of disturbing natural processes. Chief among the foreseeable challenges are increasing numbers of illegal fishers in the Southern Ocean, the persistent depletion of atmospheric ozone above the continent, the escalating numbers of tourists visiting the Antarctic Peninsula region, and increasingly grave worries that persistent global warming is causing the retreat of Antarctic glaciers and disintegration of the continent's ice shelves. Importantly, the subordination of national geopolitical ambitions to international legal rules will be necessary, but not sufficient, to reverse these problems. It should be noted, however, that beyond the Antarctic Treaty System, international legal agreements have been negotiated to address these challenges. The 1987 Montreal Protocol to the Vienna Convention on the Protection of the Ozone Layer regulates efforts to reverse ozone depletion and the 1997 Kyoto Protocol to the Climate Change Convention, for all its faults, deals with global warming. Neither of these instruments requires any geopolitical changes in the Antarctic. The question of tourism is being treated slowly through site guidelines and considerations of port state jurisdiction, adopted and enforced by the Antarctic Treaty parties. This, too, does not pose any basic change in the Antarctic geopolitical situation. Perhaps of greater interest, the Convention on Biological Diversity cannot be applied to marine life in the circumpolar Antarctic, which may prove to be a serious oversight given that the United States remains the principal nonratifying state blocking discussion of this need. The critical ingredient remains the ability and willingness of state governments to adopt and enforce regulations that compel their citizens to abide by these rules.

Christopher C. Joyner

See also **Amundsen, Roald; Antarctic Treaty; Argentina: Antarctic Program; Australia: Antarctic Program; Australasian Antarctic Expedition (1911–1914); British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); British, Australian, New Zealand Antarctic Research Expedition (BANZARE) (1929–1931); Charcot, Jean-Baptiste; Chile: Antarctic Institute; Conservation of Antarctic Fauna and Flora: Agreed Measures; Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Cook, James; Dumont d'Urville, Jules-Sébastien-César; Fisheries and Management; France: Antarctic Program; French Naval (*Astrolabe* and *Zélée*) Expedition (1837–1840); International Geophysical Year; International Whaling Commission (IWC); Mawson, Douglas; New Zealand: Antarctic Program; Norway: Antarctic Program; Norwegian *(Fram)* Expedition (1910–1912); Polar Front; Protocol on Environmental Protection to the Antarctic Treaty; Ross, James Clark; Russia: Antarctic Program; Scientific Committee on Antarctic Research (SCAR); Toothfish; United Kingdom: Antarctic Program; United States: Antarctic Program; Zooplanton and Krill**

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GEOSPACE, OBSERVING FROM ANTARCTICA

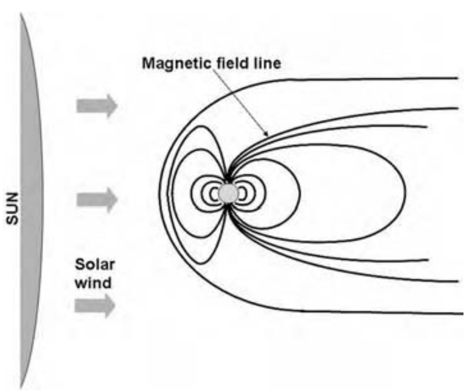
The Importance of Geospace

Geospace is the Earth's environment at the edge of space. It is primarily a vast expanse of nearly vacuous, plasma-dominated atmosphere cocooned by Earth's magnetic field. The atmosphere as most people know it, and as seen as a hazy glow in photographs taken of the edge of Earth by the space shuttle, extends from the ground up to around 100 km in altitude. Above this, however, geospace extends out to 60,000 km on the sunward side of Earth and stretches elongated on the night side to over 500,000 km—farther away than the moon, which is about 400,000 km away. Geospace is shaped like a tadpole—a stream of energetic electrons and protons from the sun, called the solar wind, flows around Earth at around 400 km per second, deforming Earth's magnetic field, which would otherwise be like that of a bar magnet, and stretching it out away from the sun. Even though geospace is so huge, if you could take all the plasma in geospace down to Earth's surface, to normal atmospheric pressure, it would all fit inside a large football stadium. Even though geospace is so empty, it is of increasing importance.

Geospace is Earth's first line of defence against matter and radiation from space; it absorbs the very short-wavelength, high-energy radiation (extreme ultraviolet) from the Sun; deflects and traps energetic electrically charged particles, preventing them from reaching the ground; and burns up meteors and space debris at the edge of the atmosphere. Geospace is the environment containing some of the major technological advances of the modern era: it is home to satellites used for communications, GPS positioning, earth observation, and military surveillance, and it is where astronauts live and work. Geospace is the closest natural plasma environment; it acts as a laboratory to understand the plasma processes that control 99.9% of the universe, and that are required to harness power from atomic fusion. Geospace poses major hazards both for space vehicles and for technology at Earth's surface; energetic particles destroy and debilitate satellites, huge electric currents generated in the aurora can put electricity power grids out of action and corrode oil pipe lines in the Arctic, and charged particles accelerated towards Earth by geospace processes can exceed the safe radiation dose for aircraft passengers at cruising altitude. Understanding these hazards and the processes that cause them is important for maintaining the continuity of satellite services and for the safety of humans and their environment on Earth. There is a growing recognition of this societal relevance, and the variability and dramatic day-to-day changes that can occur in geospace are referred to as space weather. Space weather is primarily driven by violent eruptions on the Sun related to the presence of sunspots; these dark spots, as large as ten times the diameter of Earth, frequently erupt on the Sun's surface. Sunspot magnetic fields can become unstable and their field lines can burst, hurling billions of tons of magnetised gas from the Sun's surface into space. This coronal mass ejection can hurtle towards Earth, energising the solar wind and pumping energy into geospace as it flows around it. This sparks geomagnetic storms, which can deflect compass needles by several degrees. These storms generate auroras when energetic electrons that are accelerated along Earth's magnetic field into the upper atmosphere excite oxygen and nitrogen atoms so that they emit light. Different auroral colours are characteristic of the excitation of different gases.

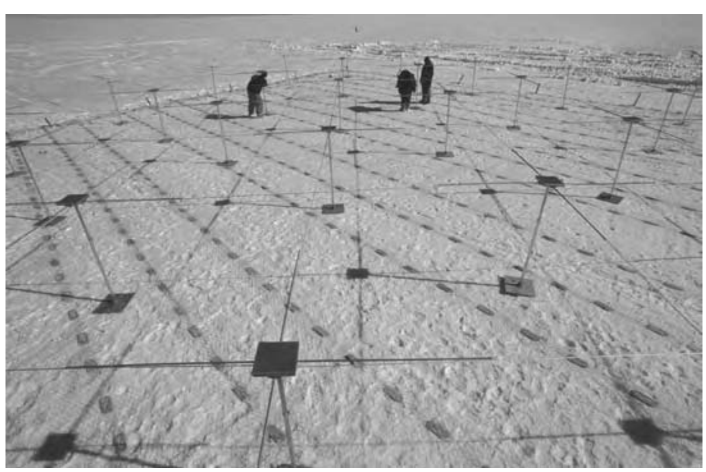
Geospace from the Ground

It is difficult to investigate geospace from satellites for several reasons. First, it is so vast that several satellites travelling in formation are required to get any real perspective on the changing environment. Secondly, satellites are always travelling rapidly across the geospace environment, so temporal and spatial changes cannot be distinguished from one another. Thirdly, the plasma is so tenuous that it is technically difficult to measure it. Observations from the ground, however, have a number of advantages over those from satellites. Plasma motion is restrained by the Earth's magnetic field—because there are almost no collisions between particles in this rarefied region and because charged particles will naturally gyrate around the magnetic field lines, any particle will remain on the same field line all the time, travelling along it rather than crossing it. Thus the plasma travels along a similar field-line geometry to that which would be mapped out by iron filings scattered around a bar magnet in the laboratory. The magnetic field lines are packed much closer together at the Earth's surface and then spread out as they extend into space. The ionosphere, between 100 and 300 km in altitude, acts like a television tube to processes going on throughout geospace. Processes that occur on the field lines many thousands of kilometres above the ground generate signatures in the ionosphere and, because the field lines in the ionosphere are much closer together than those where the processes are occurring, the picture is in miniature. A process occurring over a 5000-km-square region of geospace can typically be focussed down to a region just 200 km square in the ionosphere. This effect is accentuated in the polar regions because, as with a bar magnet, the majority of field lines enter the magnet (in our case the solid Earth) near the poles. Thus ground-based observations in either the Antarctic or the Arctic enable the study of processes in more than 90% of the volume of geospace—some million billion (1,000,000,000,000,000) cubic kilometres.



A schematic cross-section of the distortion of Earth's magnetic field by the solar wind.

The Arctic poses problems since it comprises an ocean surrounded by separated land masses. Thus sensors can only be positioned at selective longitudes, and hence time zones. Similarly sampling can only be made of part of geospace because of the physical difficulty of placing sensors at the higher latitudes. In contrast, Antarctica is a pole-centred land mass surrounded by ocean and without political boundaries. This allows the positioning of instruments at high latitude and all longitudes, giving greater coverage. As noted previously, plasma processes, which are driven primarily by the action of the solar wind, are spatially organised by the magnetic field configuration because plasma particles remain constrained to the same field line. However, processes driven by the



The antenna array of an imaging riometer at the British Antarctic Survey research station at Halley (76° S, 27° W), Antarctica.

direct action of solar radiation together with those driven by processes in the neutral atmosphere are configured by the geographic coordinate system. The geographic pole and the geomagnetic poles are offset from each other both in the Northern Hemisphere and the Southern Hemisphere. This offset allows scientists to determine whether phenomena observed in geospace are oriented in geographic coordinates or geomagnetic coordinates and hence, what the driving mechanism is—solar radiation or solar wind. In the Antarctic the offset is some 5° larger than in the Arctic and so it is easier to distinguish between the drivers from observations in the Antarctic. Thus, Antarctica is the best place on Earth for observing geospace.

Ground-based measurements from Antarctica have played a key role in understanding geospace since 1957 when the first coordinated measurements were made as part of the International Geophysical Year. Since then there have been major developments in instrument techniques that have enabled the continuous monitoring of geospace conditions from the ground; this information is used both for scientific research and to help generate forecasts of space weather. These forecasts are used for damage limitation to spacecraft, to minimise radiation exposure of astronauts and aircraft, to predict loss of terrestrial radio communications, to ensure the accuracy of magnetically guided oil drills, and to make estimates of the insurance liability regarding space technology. Many different instruments are used to remotely sense geospace from Antarctica, each with its own strengths and weaknesses; taken together, and in combination with satellite information, they allow the study of how matter and radiation from the Sun interact with the Earth system.

Geospace Observation Techniques

One of the simplest techniques is the magnetometer. This measures extremely small variations in the strength of the geomagnetic field. The strength of this field at the ground is some 35,000 nT (dependent upon location). During geomagnetic storms this can typically vary by 500 nT because of both (1) the distortion to the field produced by the strength and direction of magnetisation of the solar wind and (2) a doughnut-shaped ring of current created in geospace above the equator by electrons energised in the storm. Using an array of magnetometers hundreds of kilometres apart, the distortion that Earth's field has gone through during the storm can be reconstructed. As noted above, plasma is constrained to the field lines and so this reconstruction also defines where the plasma has moved to. While most of the plasma in the solar wind flows around geospace as if it were an obstacle in a stream, if the magnetic field within the solar wind is directed southwards, then it is able to connect with the Earth's magnetic field in a process called reconnection and plasma from the solar wind can penetrate geospace on the sunward side, enhancing the storm effect. The complex magnetometer variations during a storm allow the study of this reconnection process. Like a bar magnet, the field lines very near the poles extend a long distance away, but those nearer the middle of the magnet (i.e., Earth's equator) loop symmetrically from one half of the magnet to the other. These latter "closed" field lines resonate like the strings on a guitar but with resonant periods of a few tens of seconds. The resonant frequency is dependent upon the length of the field line and the density of the plasma through which it passes and can therefore be used to map the plasma charge density within geospace. A more complicated procedure using pairs of magnetometers to study these resonances additionally enables the mass density to be determined. Arrays of magnetometers, typically spaced a few hundred kilometres apart, are now being deployed across Antarctica to provide data throughout the majority of geospace. Many of these operate autonomously using wind and solar power; these are visited once a year by aircraft for maintenance and to download data.

A more sensitive version of the magnetometer with a very fast time resolution is designed to detect oscillations with periods of a few tenths of a second. These are generated by the gyration of protons around the Earth's field lines. Additionally, oscillations with periods of just a few seconds are generated by interactions between particles and waves and can be directly transmitted from the solar wind itself. Again, these data hold information about the plasma environment of geospace and ground-based magnetometers can provide continual measurement from a fixed location.

Latitudinal plasma density profiles through the equator can also be determined from Antarctica using naturally occurring Very Low Frequency (VLF) radio waves. There is almost no lightning in Antarctica. However, transient VLF radio spikes can be generated by lightning in the Northern Hemisphere and travel along Earth's field lines to the Antarctic. As they do so, they are dispersed—each radio frequency travels at a different velocity—and so by the time they are received by a VLF radio receiver in the Antarctic they can be heard as a whistling noise. These are called "whistlers" and their individual musical characteristics depend upon the electron density at the point farthest from Earth along the field line along which they travelled. Thus whistlers can be used to map the electron density in the equatorial plane. In addition to signals generated by lightning, artificially generated VLF waves from transmitters designed for submarine communications can also be detected after they have travelled both along the field line and around the Earth's surface to Antarctica. Measuring the difference between the radio waves taking these two different signal paths enables geospace to be observed expanding and contracting with time. It also allows the measurement of the depletion of the radiation belts, where energetic electrons can be trapped for many days, which occurs during geomagnetic storms and which precipitates high-energy electrons into the atmosphere between 50 and 100 km in altitude and changes its chemistry to produce ozone-depleting nitric oxide.

The amount of electrically charged particle precipitation generated by geomagnetic storms is measured using riometers. These instruments operate on the simple principle of using cosmic radio noise as a reference source, and measuring the changes in the strength of that on the ground. Absorption of the cosmic radio noise maximises at about 85 km in altitude, where the product of collision frequency and electron concentration, and hence removal of energy from electrons excited by the cosmic radio noise, maximises. Riometers run continuously and respond almost instantly to the electron precipitation. Imaging riometers have an array of antennae producing beams pointing in several different directions; these allow a map of the precipitation pattern to be generated, for physical boundaries within geospace to be tracked, and for drifting plasma structures to be investigated.

An alternative method of mapping the precipitation from geospace, and hence understanding space weather, is to use optical imagers. These have the disadvantage compared to riometers that they can only operate in darkness and in cloudless conditions, but they provide much finer resolution image and information on the energies of the particles. Precipitating electrons in Antarctica generate the aurora australis—the undulating curtains and radiant beams present in the aurora reflect the configuration and motion of the geomagnetic field along which the electrons travel. Different energy electrons penetrate to different depths in the atmosphere where there is a different molecular composition and hence a different-coloured emission is generated. Thus lower-energy particles lose their energy at higher altitude and produce a characteristic red glow from oxygen atoms; higher-energy particles penetrate to levels where nitrogen dominates and densities are sufficiently high that oxygen emissions are limited, so that a blue-crimson colour is generated. By using a variety of colour filters and an extremely sensitive digital camera it is possible to estimate the relative strength of different-colour light emissions, hence the relative strength of the energy dissipation at different altitudes, and thus the energy of the precipitating particles.

VLF signals propagating in the waveguide between the ionosphere and ground can provide information on the spatial size of precipitation patches. These patches perturb the VLF signal paths, changing the amplitude and phase of the signal. If sufficient transmitters and receivers exist that many listening paths cross, the pattern of perturbations in the different paths allows the size of the precipitation patch to be deduced. Recent work using Antarctic receivers has shown these precipitation patches, a consequence of lightning in the Northern Hemisphere, to be much larger than previously thought, meaning that lightning plays a significant role in emptying particles from geospace.

In the early years of Antarctic measurements, ionospheric sounders (ionosondes) were a key instrument for studying geospace. These reflect vertically transmitted radio waves off the ionosphere to determine its altitude and electron concentration, analogous to the way that ships use sound waves to echo-sound the bottom of the ocean. Later advances in ionosonde technique allowed spatial information and the velocity of ionospheric features to be determined. Because changes in the ionosphere often reflect changes in geospace higher up the field line, these studies provided basic information on geospace boundaries and electric fields. However, the spatial extent of the information was limited, covering a 600-km circle above each instrument, and the complexity of the instrument meant that it could only be operated at a fully resourced scientific base. A significant advance was achieved with the advent of high-frequency over-the-horizon radars. These transmit radio pulses horizontally so that, given the curvature of the Earth, they intercept the ionosphere at several hundred kilometres' distance from the radar, and are capable of sensing radio backscatter from ionospheric irregularities over an area of more than a million square kilometres. By measuring small changes in the frequency of the returned pulses caused by Doppler shift (similar to that experienced when the tone of a police siren changes with the relative speed of the police vehicle) it is possible to measure the speed of the irregularities as they are swept around by the ionospheric convection. This convection maps directly to electric fields in farthest geospace and, by having several similar radars around Antarctica, the ionospheric convection over most of the southern polar cap can be measured on a daily basis. There are currently five of these radar antenna arrays in Antarctica, covering the ionosphere above most of the continent; these are part of the international bipolar SuperDARN (super Dual Auroral Radar Network) system, which has fifteen radar arrays in total.

X-rays produced by the aurora in geospace cannot be measured from the ground because the X-rays are absorbed by the atmosphere and do not reach Earth's surface. As a consequence, Japan and the United States have launched huge helium-filled stratospheric balloons, some 5000 cubic metres in volume, with instrumentation on board to measure these X-rays from the stratosphere, where they are above 98% of the atmosphere. The prevailing stratospheric winds mean the balloons circumnavigate Antarctica, and the constant 24-hour summer daylight allows the balloons' electronics to be powered by solar panels. This constant sunlight also maintains a balloon at a stable temperature, which helps it maintain altitude without extreme fluctuations between night and day. Such balloons have also measured the electric field between geospace and the ground. This field is part of a global electric circuit, driven by thunderstorm activity in the tropics and by the electric field created across the polar regions when geospace interacts with the solar wind.

To reliably detect these weak currents and electric fields in this global circuit from the ground, a high, dry observation site is required. Antarctica is probably the best location in the world to make ground-based measurement of this global circuit and the influence that geospace processes have on it. Several nations are collaborating to develop an array of instruments on the Antarctic plateau; field mills will measure the vertical electric field and polished metal spheres will be suspended above the surface to measure the air–Earth current. This research may have relevance to global climate change; one scientifically controversial possibility is that changes in the global circuit could cause changes to global cloud cover, and hence climate. This collaborative work is promoted under the umbrella of the International Polar Year of 2007–2008, 50 years on from the International Geophysical Year, when the first coordinated geospace measurements from Antarctica were made.

Summary

The basic discovery and exploration phase of geospace is now largely complete. There is still much to be learnt, however, about the plasma process of reconnection, the statistical nature of geomagnetic storm occurrence, radiation belt precipitation processes, and the links between geospace, the lower atmosphere, and climate. Geospace is so vast and there are so many interacting electrodynamic processes that measurement using a single instrument and a single site can provide virtually no new information. Multiply instrumented sites and spatially distributed arrays of identical sensors are essential for major scientific progress to be made. Antarctica offers these opportunities through the advantageous geophysical locations of its research stations, the pole-centred land mass available for deployment of arrays, and the unfettered international cooperation that is traditional amongst Antarctic operators. Antarctic geospace measurements are likely to remain a key component of space weather research in the years to come.

Martin J. Jarvis

See also **Aurora; Climate; Geomagnetic Field; International Geophysical Year; Ionosphere; Meteorites; Solar Wind; Wind**

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GERMAN SOUTH POLAR *(DEUTSCHLAND)* EXPEDITION (1911–1912)

On December 14, 1911, when Roald Amundsen and his four companions reached the South Pole, *Deutschland,* the vessel of the Second German South Polar Expedition, led by Lieutenant Wilhelm Filchner, was encountering the first ice in the Weddell Sea. Filchner had earlier established his reputation as an adventurer and explorer by his solo trip across the Pamirs in 1900 and by his expedition to map the headwaters of the Huang-He in western China in 1903–1905.

It was a time when Antarctic expeditions by the Belgians, British, Swedes, French, and Scots had caught the imagination of the world. While Germany had already entered the field with Erich von Drygalsksi's First German South Polar Expedition of 1901–1903, that expedition had barely set foot on the continent and could boast of no heroic adventures. Hence, Filchner decided to mount an expedition whereby this situation might be rectified. He obtained the patronage of Prinzregent Luitpold of Bavaria and also the support of his superiors in the German Army.

Filchner's aims were entirely scientific, and he had no plans to try to reach the Pole. He suspected that East and West Antarctica were two separate landmasses, joined by the Antarctic Ice Cap, and proposed to test this hypothesis by crossing from the Weddell Sea to the Ross Sea, using horse-drawn sledges.

The expedition vessel, *Deutschland,* was a former whaler, a wooden, bark-rigged vessel with an auxiliary steam engine. Filchner was pressured to find a German captain and, despite some misgivings on his part (and even warnings), the captain chosen was naval officer Richard Vahsel, who had been second officer on Drygalski's *Gauss*. The German naval authorities authorized *Deutschland* to fly the Imperial Naval flag. This was to be the source of serious problems for Filchner, since it meant a divided command.

Filchner assembled an impressive group of scientists. Fully aware of his own (and his colleagues') lack of experience regarding ice and snow, he and five companions travelled to Svalbard in the summer of 1910 on a practice expedition. They made a pioneer traverse of Spitsbergen, traveling on glaciers, from the head of Isfjorden to Storfjorden and back.

Deutschland sailed from Bremerhaven with the main expedition in early May 1911. Having called at Buenos Aires (where the expedition's Greenland dogs were embarked) and Montevideo, it reached Grytviken in South Georgia on October 21. Here Captain Carl Larsen, manager of the whaling station at Grytviken, put his yacht, *Undine,* at Filchner's disposal, to survey the coasts of South Georgia, while *Deutschland* surveyed the northern islands of the South Sandwich Islands.

Having embarked the expedition's twelve Manchurian ponies, *Deutschland* put to sea from Grytviken, bound for the Weddell Sea, on December 11, 1911. It entered the pack ice on December 14 and for over a month fought its way slowly south, emerging into open water on January 29, 1912. On the next day, ice-covered land, the southern continuation of Coats Land, was sighted to the southeast and was named Prinzregent Luitpold Land.

On January 31, at 77°44′ S, the ship's further progress was blocked by the front of an extensive ice shelf stretching from the ice cap westwards to the horizon. Later named the Filchner Ice Shelf, along with the Ronne Ice Shelf farther west, it forms the southern limit of the Weddell Sea. The angle between ice shelf and ice cap was named Vahsel Bay, after the captain.

In that angle lay a tabular iceberg that had broken away from the ice shelf but still abutted against it. With an assurance from the expedition's ice expert, Paul Bjørvik, relayed by Captain Vahsel, that there was little chance of the iceberg's breaking away, Filchner decided to erect his base hut on its surface, since it offered a suitable landing site. Offloading of equipment and supplies began on February 9; by the evening of February 17, the shell of the hut was complete and a large amount of stores and equipment had been landed. But on the night of February 17–18, with a high spring tide, the iceberg broke adrift and began floating out to sea, followed by a minor armada of other tabular bergs. In the midst of this crisis Filchner learned that Bjørvik had warned the captain against this choice of a site for the base camp.

Work began to salvage as much as possible, and ultimately only the shell of the hut, one and a half tonnes of coal, five sledges, and some food had to be abandoned. Undeterred, Filchner set about establishing a second base camp on the ice cap, east of Vahsel Bay, and by the evening of February 28 had made all the preparations. But new ice began to form the next morning, and on March 2 Captain Vahsel insisted that to prevent his ship from becoming beset, it must leave immediately. *Deutschland* managed to make some progress north, but by March 15 was solidly beset, and a winter adrift in the ice of the Weddell Sea had begun. An array of buildings and instrument shelters was erected on the ice around the ship and a comprehensive program of scientific work began. In late June, when the ship was fairly close to the alleged position of "Morrell Land," reported by the American Benjamin Morrell in 1823, Filchner and two companions made a week-long sledge trip to the alleged location of this landmass and proved that it did not exist.

On August 8, Captain Vahsel, who had been sick for some time, died of syphilis and was buried at sea. Possibly his bizarre decisions about the landing may be attributed to the neurological side effects of the terminal stages of the disease.

As the ice began to break up, the ship managed to free itself on November 26 and got under way under the command of the first officer, Wilhelm Lorenz. By December 19 they were back at Grytviken.

Despite having fallen far short of Filchner's goals, the expedition had made some useful contributions to both geographical exploration (the surveys of South Georgia and the South Sandwich Islands, the discovery of Luitpold Land and the Filchner Ice Shelf, and the removal of "Morrell Land" from the map) and to meteorology and geomagnetic studies on the basis of the work during the ice drift.

William Barr

See also **Amundsen, Roald; Drygalski, Erich von; Filchner, Wilhelm; German South Polar *(Gauss)* Expedition (1901–1903); Larsen, Carl Anton; South Georgia; South Sandwich Islands; Weddell Sea**

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GERMAN SOUTH POLAR *(GAUSS)* EXPEDITION (1901–1903)

The noted German scientist Georg von Neumayer (1826–1909) began promoting the dispatch of a German expedition to Antarctica as early as 1865, but it was not until three decades later that he finally succeeded in setting up a German Commission for South Polar Exploration, of which he became chairman.

During the Sixth International Geographical Congress—held in London in 1895 under the presidency of Clements Markham—a resolution was passed that the exploration of the Antarctic regions was the greatest piece of geographical exploration still to be undertaken. Neumayer finally had the opportunity to push forward the plan of a German expedition. However, it was not until February 19, 1898 that the geographer Erich von Drygalski (1865–1949) was elected leader of the expedition. He had already gained polar experience by leading two expeditions to Greenland (1891 and 1892–1893). Now the responsibility changed from the Commission to Drygalski. Nevertheless, he was bound to Neumayer's travel route via Îles Kerguelen.

In April 1899, the expedition was financially secured by an Imperial internal budget, to be administered by the Ministry of the Interior. During the Seventh International Geographical Congress—held in Berlin in 1899 under the presidency of Ferdinand Freiherr von Richthofen (1833–1905)—Markham defined the fields of work of the German and British expeditions. He divided Antarctica into four quadrants starting at the 0° Greenwich meridian. According to the British tradition of exploration, he assigned the Ross and Victoria quadrants to Britain and the Weddell and Enderby quadrants to Germany.

Drygalski proposed a collaboration with the British expedition and recommended the organisation of simultaneous observations during the expeditions and at suitable locations outside the Antarctic. Magnetic term days were defined on the first and fifteenth of each month from February 1, 1902 until February 15, 1903. Meteorological observations were to be made from October 1, 1901 until March 31, 1903, including on all merchant and navy ships sailing on a route south of 30° S. When a French expedition under Jean-Baptiste Charcot (1867–1936) followed in 1903, the international cooperation was expanded until March 31, 1904.

The Imperial Admiralty was involved in the planning of the expedition, but only two of the seamen came from the navy. The building of the first German polar research vessel, *Gauss,* was taken over by the Nautical Division of the Reich Marine Office at Howaldt Warf in Kiel. *Gauss* was to serve as the flagship of German science, with an iron-free area for magnetic investigations on the ocean and a body similar to the Norwegian *Fram*.

Drygalski became an official representative of the Ministry of the Interior, and the expedition was allowed to sail under the official flag of the Ministry. A special decree allowed the ship's commander, Hans Ruser (1863–1930), the right to refuse Drygalski's orders only in cases where he perceived an immediate threat to life and property aboard.

The instructions given by Emperor Wilhelm II were rather general, referring only to a few fundamental questions and leaving the freedom of action that Drygalski desired. The program followed Alexander von Humboldt's (1769–1859) ideas of comprehensive investigation of an unknown area concerning the three elements—earth, water, and air—and the living world. Due to this, geology, geography, earth-magnetism, oceanography, meteorology, and biology played major roles. Five officers, five scientists, and twenty-two seamen were aboard. Drygalski and biologist Ernst Vanhöffen (1858–1918) had already wintered together at Greenland 9 years before, and the Norwegian ice pilot Paul Bjørvik (1857–1932) was a very experienced Arctic veteran.

On August 11, 1901, *Gauss* set sail at Kiel for an unknown destination near 90° E, far to the south. A base station not being influenced by Antarctica was established at Observatory Bay on Île Kerguelen. Unfortunately, on February 22, 1902, *Gauss* was beset by ice close to the Antarctic Circle at 66°2′ S, 89°38′ E, 85 km off the Antarctic coast. The expedition members were lucky that the ice was not drifting, so they could establish a fixed winter station on sea ice 385 m above sea bottom. They discovered the ice-covered coast of Kaiser Wilhelm II Land and an ice-free extinct volcano, which they named Gaussberg. After 50 weeks of captivity, the ship finally came free on February 8,

1903. Drygalski tried in vain to approach higher latitudes west of their wintering place to give an answer to the unsolved problem of the existence of a coastal connection between Kemp Land and Enderby Land or of a drift that would take them into the Weddell Sea. But a second attempt to go south was not allowed by the Ministry of the Interior, because the budget was already exhausted. So the expedition was forced to sail home as soon as possible, arriving at Kiel on November 25, 1903.

The welcome for the returning expedition was not overwhelming, because Emperor Wilhelm II had been disappointed in their results, as Robert Falcon Scott had established a farthest south of 82°17′ S on the concurrent British National Antarctic Expedition. In early 1900, Antarctica had become a playground of politics, and many believed the goal there was to set the flag as far south as possible. Being trapped at the Antarctic Circle was seen as a national failure, when geographical achievements were considered much more valuable than thoroughly measured scientific data, which had to be analysed and published over a period of decades (three in this case). To avoid costs for maintenance, *Gauss* was sold for 75,000 Canadian dollars and used under its new name *Arctic* for the Canadian Coast Guard by Joseph E. Bernier (1852–1934).

Despite the political controversies, data of the collaboration were exchanged and synoptic charts plotted for meteorology and magnetism. Nine hundred thirteen daily synoptic weather charts were produced in Germany, which were processed to thirty maps of monthly means and several other quarterly, seasonal, and yearly charts. Geographical investigations indicated that Antarctica was a big continent covered by ice. The mean height of the continent was assessed as 2000 m $\pm$ 200 m. Data of the magnetic field of the Earth improved the charts of the southern seas. The biological collection of 4030 species was outstanding, and 1470 species were described for the first time. The most striking result of the expedition indicated a stratification of four different water layers in the southern Indian Ocean. All results were published in a process extending until 1929, filling twenty volumes and two atlases. Retrospectively, Drygalski's expedition was labelled "universitas antarctica."

The German initiative of a scientific cooperation in Antarctica became a model for further research, which culminated in the International Geophysical Year of 1957–1958.

Cornelia Lüdecke

See also **British National Antarctic *(Discovery)* Expedition (1901–1904); Bruce, William Speirs; Charcot, Jean-Baptiste; Drygalski, Erich von; French Antarctic (Français) Expedition (1903–1905); Kerguelen Islands (Îles Kerguelen); International Geophysical Year; Markham, Clements; Neumayer, Georg von; Nordenskjöld, Otto; Scott, Robert Falcon; Scottish National Antarctic Expedition (1902–1904); Swedish South Polar Expedition (1901–1904).**

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GERMAN SOUTH POLAR *(SCHWABENLAND)* EXPEDITION (1938–1939)

When agriculture had to be rebuilt in Germany following World War I, sperm oil became the most important raw material for the production of margarine and soaps. During the early years of the Third Reich, the Fat Plan was designed to solve the need for fats, but it was not successful and was ultimately replaced by the New Plan, which promoted an increase of home-grown fat production. One of the issues that had to be resolved to do this was decreasing German dependence on foreign sperm oil. Germany was the second largest importer of Norwegian sperm oil—about 200,000 tons per year—which caused a tremendous outflow of capital. To resolve this problem, a German whaling fleet was set up and put to sea during the austral summer of 1937–1938.

Helmuth Wohlthat (1893–1952) was totally familiar with the need for fat and with the problems of foreign exchange when he became ministerial director for special employment under the Representative of the Four-Year Plan, Hermann Göring (1893–1946).

Following the return of the whaling fleet in spring 1938, Wohlthat initiated the third German Antarctic expedition, the goal of which was to establish self-sufficiency in sperm oil within the outlines of Göring's Four-Year Plan. The main part of the expedition plan was to occupy a position on the Antarctic coast, where a secure base for German whaling could be established. At the time, on the return journey, secret military problems concerning the future establishment of a naval base on the island of Trinidad, or Martin Vaz northwest of Rio de Janeiro, could also be resolved. Thus, with this expedition, German Antarctic exploration was launched again, although it was driven by economic and political aspects during the Third Reich, rather than by pure scientific research.

Alfred Ritscher (1879–1963) was the only possible leader for the expedition. He was captain and aircraft pilot, after having already gained polar experience during the Schröder-Stranz expedition to Spitsbergen in 1912. He was released from the high command of the German Navy so that in an extremely short time he could prepare the expedition with two Dornier-10-t-Wal seaplanes, *Boreas* and *Passat,* aboard the catapult ship *Schwabenland.*

On December 17, 1938, the expedition left Hamburg. The ship traveled south along the Greenwich meridian, reaching the belt of pack ice around the Antarctic coast on January 19, 1939. However, the region between Coats Land in the West and 45° E—which included the area in which the Germans hoped to carry out their mission—had been put under Norwegian sovereignty through a royal decree five days previous. Nevertheless, by February 6, 1939, six reconnaissance flights and eight flights for photogrammetric surveys of the region east of the Weddell Sea between 6° W and 18° E had been performed. This gave the Germans the data for the construction of a map of Neuschwabenland on the scale 1:1,500,000.

Altogether 350,000 km^2 of uncharted territory were carefully covered by aerial survey and a further 600,000 km^2 were seen as well. The expedition discovered Neuschwabenland, with its ice-free mountain ranges of up to 3000 m in height in the Wohlthat Mountains, including the spectacular Schirmacheroasen (in recent decades one of the centers of German Antarctic scientific research). Later that year, the outbreak of World War II stopped all further attempts to continue exploration or research related to the establishment of an Antarctic base and the securing of German whaling.

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See also **Oases; Whaling, History of**

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GERMANY: ANTARCTIC PROGRAM

Germany has been a consultative party to the Antarctic Treaty since 1981 and maintains a long-term commitment to scientific research in Antarctica. The Alfred Wegener Institute for Polar and Marine Research (AWI), as the national coordinator, enables Germany to maintain this role from its research and long-term monitoring and survey activities. It provides the main mobile and stationary infrastructure for Antarctic research, and maintains the permanent German presence in Antarctica. AWI closely cooperates with national Antarctic programmes of the consultative parties and provides members to the related international organizations within the Antarctic Treaty System. In addition to AWI, the Federal Institute for Geosciences and Natural Resources (BGR), the German Aerospace Centre (DLR), and the Federal Agency for Cartography and Geodesy (BKG) perform long-term research activities in Antarctica.

The research and supply vessel RV *Polarstern,* commissioned in 1982, is the major research tool for German marine polar activities. The advanced scientific and technical equipment and ability to navigate in heavy ice conditions in almost all regions of the Arctic and Antarctic oceans make it a leading platform of the international polar research fleet. It provides ideal working conditions for biological, geological, geophysical, glaciological, chemical, oceanographic, and meteorological research. Nine scientific laboratories, hydroacoustic sounding systems, winches, fiberoptic networks, and data-acquisition systems are installed. Refrigerated rooms and aquaria permit the transport of samples and living marine fauna. Facilities such as flight control, hangar, helideck, and refuelling facilities are available for two helicopters (BO 105 CBS 5) used for sea-ice reconnaissance, transport of personnel, and scientific observations. The weather station provides forecast information and satellite imagery on sea-ice distributions. Hydroacoustic navigation aids have been installed to deploy remotely controlled underwater vehicles. The overall length is 118 m and maximum beam 25 m. Displacement and draught are 17,300 tons and 11.2 m, respectively. Propulsion is performed by 4 diesel engines providing approximately 14,000 KW. The maximum speed is 16 knots. Bow and stern thrusters assist to manoeuvre the ship, if required for special observations or for unloading operations at the ice shelf margin. The overall capacity is 124 persons with 38 to 44 berths for crew. About fifty to seventy scientists can be accommodated and provided with working facilities on board. RV *Polarstern* is managed by AWI and spends approximately 320 days at sea each year. By 2006 the vessel had completed twenty-three Antarctic expeditions and twenty-one Arctic expeditions with two visits to the North Pole, in September 1991 and January 2001, respectively. Antarctic cruises have gone to the Weddell, Bellingshausen, and Amundsen seas as well as waters around the Antarctic Peninsula and Weddell Sea, where the supply of Neumayer Station is a yearly task.

The Neumayer station (70°39′ S, 08°15′ W, 40 m a.s.l.) is the permanently occupied German research station located at the Eckström ice shelf of Atka Bay. The station was commissioned in 1992 and replaced the original Georg von Neumayer station commissioned in 1981. Since that time scientific observatories have been continuously operated for meteorology, atmospheric chemistry, and geomagnetic and seismological data. These long-term records are routinely fed into the respective international networks. Neumayer station provides highly recognized contributions to climate research, in particular studies of the ozone layer and to investigations of the regional present-day tectonic and seismic activity. In 2003 one of the four Infrasound Arrays in Antarctica was installed at the station as part of the global International Monitoring System (IMS) of the Comprehensive Test Ban Treaty Organisation (CTBTO) controlling the adherence of the Comprehensive Nuclear Test Ban Treaty. The Neumayer station is constructed on ice. The central facility is a steel tube system consisting of two main tubes (eastern tube 82 m in length, western tube 92 m), a 92-m-long cross tube, and a garage for polar vehicles. The tubes' diameters are between 8 and 8.4 m. The gross area within the tubes is about 3400 square meters. Founded on ice, the current Neumayer station has a finite lifetime of about 15 years. It will have to be replaced by a new station in 2008, in order to continue long-term scientific observations and commitments.

The wintering staff consists of four scientists, three technicians, a cook, and a physician. During the Antarctic summer season about thirty to fifty scientists and technicians are temporarily at the station. Neumayer is the operational base for scientific and supply aircraft missions and deep-field traverses. The Dornier 228-101 aircraft *Polar 2* (commissioned in 1983) is regularly operated in Antarctica during the summer season. The combined wheel and ski gear enables take-off and landing at gravel strips and even unprepared snow surfaces. The slow flight speed makes it an effective tool for airborne geophysical and glaciological survey missions as well as meteorological and air chemistry studies.

The polar vehicle fleet is composed of "Pisten-Bully" tracked vehicles specially adapted to withstand the stress of pulling sledges for heavy loads and sundry other equipment necessary to ensure optimal working conditions for scientists as well as their personal safety. They are equipped with GPS navigation and appropriate communication equipment and can operate year-round, allowing serving of deep-field observatory installations. Every summer season the Kohnen station (75° S, 00° E, 2892 m a.s.l.), the first German summer base on the Antarctic inland ice plateau of Dronning Maud Land, is also supplied by the vehicle fleet. The distance between Neumayer and Kohnen is 470 miles (757 km). Depending on weather conditions a traverse takes 9 to 14 days. The Kohnen Station was established in 2000 primarily as the second base for deep ice-core drilling in the frame of the European Project on Ice Coring in Antarctica (EPICA). In the course of six summer seasons a 2780-m ice core was drilled. About 400,000 years of climate history could be studied from this ice core. Kohnen Station will serve at least for the next decade for a number of summer-only investigations. It consists of a 32-m-long and 8-m-wide platform on steel pillars where 11 prefabricated container modules are mounted. Up to twenty individuals can be accommodated (see http://www.awi-bremerhaven.de/Polar/Kohnen/index.html).

Further research facilities of the German Antarctic program were established in cooperation with other national programs. The Dallmann Laboratory is operated as an annex station at the Argentinian Jubany station at King George Island (62°14′ S, 58°14′ W, 15 m a.s.l.). It was established in 1994 as an international laboratory funded by the Instituto Antartico Argentino (IAA), The Netherlands Council of Earth and Life Sciences (NWO), and AWI. Since then about twenty-five to thirty-five scientists have been working there each summer season. Besides special laboratories for marine-biological work, scuba diving facilities are available (see http://www.awi-bremerhaven.de/Polar/dallmann.html). The German Antarctic Receiving Station (GARS) is an annex station at the Chilean station General Bernardo O'Higgins (63°19′ S; 57°54′ W). Since October 1991 GARS has been cooperatively operated and managed by the German Aerospace Center (DLR) and the Instituto Antartico Chileno (INACH). GARS is part of the international ground segment for remote sensing in the southern hemisphere. The station is an important European research platform for acquisition, precision processing, and cataloguing of satellite data. The station has its own specially constructed radio-telescope with a 9-m-diameter mirror for reception of satellite data and performance of geodetic surveys using Very Long Baseline Interferometry (VLBI). Up to fifteen scientists can be accommodated. The station is only occupied about 120 days per year.

Antarctic research in Germany has a long tradition. The historical record features famous names as Johann and Georg Forster, who participated on the expedition of James Cook aboard the ships *Resolution* and *Adventure,* but also Eduard Dallmann, Erich von Drygalski, Wilhelm Filchner, and Alfred Ritscher as expedition leaders and scientists. Modern international Antarctic research commenced with the International Geophysical Year (IGY) of 1957–1958, following which both German governments began Antarctic activities. After 1959 guest scientists from East Germany stayed for wintering and worked in the field at several Russian Antarctic stations. Likewise, scientists from West Germany joined US expeditions.

In 1974 the Antarctic Treaty was signed by East Germany. It received consultative status in 1988. The first permanently occupied Research Base—later named Georg Forster Station—was established in the Schirmacher Oasis in 1976. At that time the construction concept was pioneering. Prefabricated container modules serving as laboratories, power plants, and accommodations were carried on sledges over a distance of 120 km into the Schirmacher Oasis and assembled as a research base within 6 weeks. Since then the station has been permanently occupied and operated—as an annex to the Russian Novolazarevskaya Station until 1987 and then as a German Antarctic station until 1993. Long-term studies of magnetospheric–ionospheric processes, geophysical investigations, biological studies, and sea-ice observations using satellite imaging were performed. In 1985 the station became known to the international scientific community when the vertical extension of the ozone hole in the southern polar stratosphere was first recorded by regular balloon-borne ozone observations. These regular ozone measurements were performed until 1992 and continued at Neumayer station afterwards.

In West Germany, the first marine-biological expeditions were performed in 1975–1976 and 1977–1978. The Antarctic Research Programme of the Federal Republic of Germany was established in 1978 and the Antarctic Treaty was signed in 1979. BGR performed the first terrestrial expedition (GANOVEX I) into North Victoria Land in 1979–1980. Germany received consultative status in 1982 after the foundation of AWI in 1980, construction of the permanently occupied research station Georg von Neumayer in 1981, and commissioning of *Polarstern* in 1982. The budget for AWI's Antarctic research, including personnel, operations, and investment, increased from 39 million Euros in 2000 to about 49 million Euros in 2005. AWI has also been successful in applying for funding from the European Union. The annual budgets are about 2 million Euros for BGR and about 1.5 million Euros for DLR/BKG Antarctic activities. Project funding of about 3 million Euros is via the DFG within the framework of applications for the Priority Program Antarctic Research or via the normal funding channels. DFG funding is of great importance, as it enables the participation of a number of university working groups on the complex marine and terrestrial Antarctic expeditions. Altogether about 250 to 300 German scientists and technicians work in Antarctica every year. Scientific objectives and logistical performance of all German Antarctic operations by ship, aircraft, and land vehicles, as well as works at stations and in the field, are in line with the international regulations of the Antarctic Treaty System. A national environmental protection act (AUG) is in force according to the Protocol on Environmental Protection to the Antarctic Treaty, which requires the approval of all research activities in Antarctica by the Federal Environmental Agency.

Hartwig Gernandt

See also **Alfred Wegener Institute for Polar and Marine Research, Germany; Antarctic Treaty System; Cook, James; Dallmann, Eduard; Drygalski, Erich von; Filchner, Wilhelm; German South Polar *(Deutschland)* Expedition (1911–1912); German South Polar *(Gauss)* Expedition (1901–1903); International Geophysical Year; Oases; Protocol on Environmental Protection to the Antarctic Treaty**

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GIGANTISM

Polar Gigantism in Antarctic Benthos

Scientists on turn-of-the-twentieth-century voyages to Antarctica marvelled over isopods the size of a human hand and sea spiders (pycnogonids) even larger. Modern visitors may occasionally observe the sea surface from boats and see ctenophores (comb-jellies) up to 0.5 m long, despite being only a few cells thick. Several benthic invertebrate groups tend towards larger sizes at high latitudes. Polar gigantism has been described for several marine Antarctic taxa including Porifera, Nematoda, Nemertea, Ascidiacea, Polychaeta, and Pycnogonida, as well as many crustaceans (Cirripeda, Ostracoda, Copepoda, Isopoda, and Amphipoda). Polar dwarfism has also been described, but only for gastropods, bivalves, and fish. Low temperature and its effects on growth have long been the most widely quoted factors in explaining polar gigantism. However, a thorough study of crustacean Amphipods recently showed oxygen to be a key factor.

This work was based on length measurements of over 2000 species of benthic amphipods, divided over sixteen geographical localities from the tropics to the poles. Furthermore, the study included fresh (Lake Baikal), brackish (Caspian Sea), and high-altitude (Lake Titicaca) waters, allowing the decoupling of temperature and oxygen concentration.

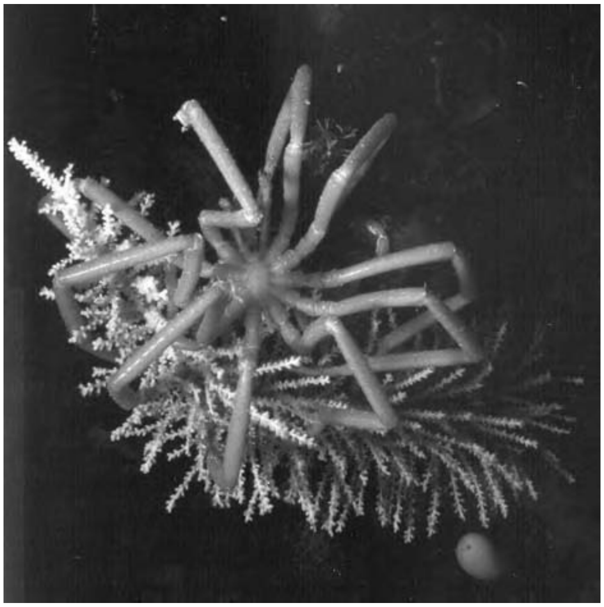
Analysing size spectra of these sixteen amphipod fauna showed that, with increased oxygen concentration, size increased slightly in small species, more in mid-size species, and maximally in the largest species. The hypothesis for explaining this relationship is based on two physiological factors. First, amphipods lack an efficient blood-pigment and carry oxygen around the body in dissolved form. Secondly, surface:volume ratio decreases with increasing size. At some point, an upper threshold is reached, where the respiratory surface limits further oxygen supply for the volume of metabolically active tissues. Therefore, oxygen availability acts not as a selection pressure on size, but as a ceiling limiting the maximum potential size amphipods can reach.

The relationship has been observed across taxonomic levels, from order to species. These results suggest that each species has an optimum size, which is closely linked to metabolic cost. Both of these are limited by the amount of oxygen available in the environment.

A similar trend linking size and oxygen has been demonstrated in nematodes and deep-sea gastropods. A latitudinal cline in maximum size was described for caridean shrimps and brachyuran crabs, but no firm conclusions were drawn. However, oxygen availability was probably important. The close relationship between oxygen concentration and maximum size remains unexplored in other taxa. The best Antarctic candidates are pycnogonids, certain crustaceans (isopods, mysids, and pelagic copepods), nemerteans, and freshwater mites. However, recent work has shown that generations of flies grown in reduced oxygen get smaller.

Oxygen availability is also important in setting upper temperature limits for survival in marine species. Furthermore, poor aerobic capacities cause Antarctic benthic species to lose the ability to do work with very small incremental changes in temperature, and interestingly, the largest animals are the first ones affected. An important future consequence for the limitation of size and temperature tolerance related to oxygen is that global warming is likely to have more dramatic consequences for Antarctic marine animals than fauna from other latitudes, and the largest species are possibly the most vulnerable.

Gauthier Chapelle and Lloyd Peck



Gigantism, as shown in the common giant sea spider (pycnogonid) *Decalopoda australis*. (Photo: David K. Barnes.)

See also **Benthic Communities in the Southern Ocean; Copepods; Deep Sea; Growth; Nematodes; Parasitic Insects: Mites and Ticks**

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GLACIAL GEOLOGY

Glacial geology is the study of sediments and landforms produced by glaciers as they flow over the Earth's surface. The processes that lead to the creation of glacial sediments and landforms can be divided into erosion, transportation, and deposition.

The principal forms of glacial erosion are (1) plucking, which occurs when blocks of material are pulled from the bed of a glacier when water freezes, and (2) abrasion, which is caused by mechanical wear of the glacier bed by rock particles held within ice at the bottom of the glacier. In Antarctica it is thought that the rates of glacial erosion are considerably lower than in other glaciated environments, partly because most ice flows very slowly and partly because of the low temperature of the ice. The exceptions to this are the ice streams that flow at considerably high velocities and are warmer than the surrounding ice. One of the contemporary debates concerning erosion processes concerns whether cold glaciers (those with beds well below the freezing point) are capable of basal erosion. Research in the Northern Hemisphere has suggested that cold glaciers may preserve landscapes rather than erode them (Kleman and Borgstrom 1994). Studies of glaciers in Antarctica with basal temperatures around –18°C show that such cold-based glaciers can deform and erode their beds (Atkins et al. 2002; Fitzsimons et al. 1999). This is most likely where glaciers rest on frozen sand and gravel, which can be eroded by plucking and incorporated in the base of glaciers. In Antarctica there are few of the classical features of glacial erosion that are associated with temperate mountainous environments. The absence of such landforms is in large measure due to the fact that most of Antarctica remains heavily glaciated and the eroded landforms lie beneath the modern ice sheets. In addition those parts of the periphery of Antarctica that were glaciated have a subdued topography, such as the east Antarctic coastal oases in the Vestfold, Larsemann, and Bunger Hills, because they were completely inundated by ice.

Material that is eroded by glaciers can be transported in three positions: on top of the glacier (supraglacial), within the glacier (englacial), and close to the bed of a glacier (subglacial). In Antarctica it is very rare for material to be transported in a supraglacial position because so little rock protrudes from the glaciers. The exceptions are nunataks, which are isolated peaks that rise above the ice surface. Where this occurs it is possible that debris from the nunatak will be transported on the glacier surface in a line that extends downstream from the rock outcrop. In Antarctic glaciers, the bulk of debris is transported close to the beds of glaciers. Ice that is adjacent to the glacier bed is often characterised by relatively high concentrations of debris (typically 10% by volume) carried in a layered zone up to a few metres thick. This basal ice forms at the glacier bed through a combination of thermal and mechanical processes that link the glacier to its bed. These thermal and mechanical processes result in several characteristics, including layers and/or lenses of debris entrained from the bed, deformation structures including folds and faults, relatively high solute concentrations, and unusual gas compositions that distinguish the ice from ice that has formed solely by the firnification of snow at the glacier surface. Because of its position close to the glacier bed, basal ice is an important component in the rheological behaviour of glaciers. The basal zones of glaciers are generally only visible at terrestrial (on land) glacier margins, although occasionally icebergs with prominent black and white layers that are characteristic of basal ice are sighted in the Southern Ocean.

Material transported by glaciers is deposited by several processes, including lodgement, melt, and sublimation. Lodgement is a process that occurs beneath flowing ice where particles held within the ice are dragged along the bed until the drag exceeds the forward motion of the ice, at which time the particle is deposited. Deposition by melting occurs where relatively warm conditions are found at glacier margins, beneath relatively fast-flowing glaciers and beneath ice that comes into contact with water. The main product of melting of debris-bearing ice is an unsorted or poorly sorted deposit that is referred to as a till or diamict. The particularly cold and dry nature of the climate in Antarctica means that melting is much less important than in glacial environments in lower latitudes. For example, in the Dry Valleys, sublimation (the direct transfer of ice into water vapour without a liquid phase) is thought to constitute from 40% to 80% of total ice loss by glaciers (Lewis et al. 1998). Because of the importance of the process of sublimation, it has been argued that the landforms and sediments produced by glaciers are different from those produced in Arctic and temperate environments (Shaw 1977), although Fitzsimons (2003) has argued that landforms and sediments associated with polar continental glacier margins such as Antarctica are not fundamentally different from other glaciated environments on earth. In the more northerly parts of Antarctica, such as the coastal oases and Antarctic Peninsula, melting becomes more important because of the warmer temperatures, and when debris is released it often slumps, slides, and flows because it becomes saturated. Where material transported and deposited by glaciers becomes concentrated, distinctive landforms called moraines form. The most prominent moraines in Antarctica occur in the coastal oases such as the Vestfold, Bunger, and Larsemann hills or in ice-free areas such as the McMurdo Dry Valleys. In these locations, end moraines record the former positions of glacier margins. In the case of the coastal oases, the moraines are a few thousand years old, whereas in the Dry Valleys the landforms may rest relatively undisturbed for several million years. Two contemporary problems that have occupied glacial geologists are the behaviour of the Antarctic ice sheets during the last glacial maximum (20,000 years before present) and the initiation of glaciation in Antarctica. Evidence from the McMurdo Dry Valleys indicates that during the last glacial maximum the Ross Ice Sheet thickened, advanced into the valley forming Glacial Lake Washburn, and deposited the Ross Sea Drift. The Ross Sea Drift consists of numerous small moraines and eskers that form narrow sinuous ridges deposited by streams that formed within or under the melting ice (Denton and Marchant 2000). Other prominent landforms in this area are lake shorelines that record the level of the now-drained Glacial Lake Washburn, and perched deltas that record the positions of streams that flowed into the lake.

Another focus of research in glacial geology in Antarctica has been understanding the origin of the ice sheets and ice-sheet behaviour over the last 35 million years. The Cape Roberts Project was a cooperative venture between seven countries—Australia, Britain, Germany, Italy, the Netherlands, New Zealand, and the United States of America. It was designed to investigate the early history of the East Antarctic ice sheet and the West Antarctic Rift System by coring sedimentary strata at 77° S, at the edge of the present ice sheet close to the Transantarctic Mountains. The cores provide a 1500-m record of climate and mountain/basin history for the period from 34 to 17 Ma. They show that this sector of East Antarctica had a cool temperate to periglacial climate with low woodland vegetation from 34 to 24 Ma, at which time mountain glaciers and possibly inland ice sheets were releasing icebergs to the Ross Sea. The cores also show that the period from 17 to 24 million years before present was cooler, allowing a low-growing sparse tundra on the adjacent mountains, along with periods of more extensive grounded ice. And finally, they show that the Transantarctic Mountains had achieved most of their present height by 34 Ma (Nash et al. 2001). The Cape Roberts Project has been succeeded by the ANDRILL project, which is focussed on reconstructing 35 million years of ice-sheet behaviour at the Antarctic continental margin.

The lack of ice-free land in Antarctica means that most products of glacial erosion and transportation are deposited into the ocean surrounding Antarctica. The vast bulk of this glaciomarine material is deposited close to the position at which the ice begins to float (the grounding line), where it forms subaqueous (underwater) moraines and fans. Fine suspended sediment may be transported into deeper water together with debris flows, which are sediment–water mixtures that flow under the influence of gravity. The other main form of transportation of debris into deeper water occurs where outlet glaciers containing debris produce icebergs that subsequently melt, resulting in the release of debris into the ocean (Anderson et al. 1980). The deposit produced by this process is known as ice-rafted debris and it consists of fine marine sediment with occasional coarse particles up to the sizes of boulders.

Ice-free areas that are adjacent to, but not covered by, glaciers are often referred to as periglacial areas and are characterised by low temperatures and permanently frozen ground (permafrost) that has a thin surface layer (an active layer) that may thaw during the short summer period. These areas are covered by cold desert soils that often show signs of long periods of weathering, some chemical alteration, and biological colonization and are often associated with very stable landscapes that have not been significantly disturbed for millions of years (Campbell and Claridge 1987).

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See also **Antarctic Ice Sheet: Definitions and Description; Dry Valleys; Glaciers and Ice Streams; Ice Ages; Ice–Rock Interface; Ice Sheet Mass Balance; Icebergs; Oases; Ross Ice Shelf; Southern Ocean: Climate Change and Variability; Subglacial Lakes; Surface Features**

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GLACIERS AND ICE STREAMS

Glacier ice is the largest reservoir of fresh water on Earth. About 90% of that reservoir is located in Antarctica, in the east and west Antarctic ice sheets, and in ice caps and glaciers on the Antarctic Peninsula.

Glaciers typically form in mountain valleys where snow persists throughout the summer. Over time, the accumulated snow compacts under the weight of snow above it, becomes more dense, and turns into glacier ice. Gravity, which forces a sloping ice surface to spread out over time, causes the glacier to flow downhill towards lower elevations. When more mass is gained by snow accumulation than is lost to melting, sublimation (a phase change directly from solid to vapor), or, in some locations, iceberg calving, the glacier grows larger. When more mass is lost than gained, the glacier retreats. Mountain glaciers may coalesce at high altitudes to form small ice caps or large ice sheets. Cycles of glacier growth and retreat are controlled by the environment and by glacier flow.

The rate at which glacier ice flows depends on its geometry and on the characteristics of the bed over which the ice moves. Steeper surface slope and greater thickness tend to produce faster ice flow. The effects of basal conditions are more complex. Rigid bedrock surfaces resist glacier flow more readily than do weak unconsolidated sediments. Meltwater at the interface between the base of the ice and the underlying material is another important factor. Both soft sediments and large basal water pressures tend to enhance ice flow, in a group of processes called basal sliding. Together, these characteristics of the ice and the bed over which it flows produce a wide range of glacier flow styles.

According to the physical laws of motion, the forces acting on a steadily moving body, such as a glacier, must balance. Glacier ice is put in motion by a gravitational driving force that is the product of ice surface slope, thickness, density, and the acceleration due to gravity. The driving force is resisted, or balanced, by drag forces wherever the glacier ice must push past another material, such as the bed beneath the ice, valley walls, and obstacles in the path of the flowing ice, and by longitudinal pushes and pulls within the ice. The application of a driving stress causes ice to deform, flowing like a viscous fluid. The deformation rate depends on temperature; warmer ice responds more rapidly than colder ice.

The relative importance of the various resistive forces determines the style with which a particular glacier's ice flows. Where the basal drag is large, ice deforms by vertical shearing, an internal deformation of the ice crystals much like the shearing of a stack of cards when a traction is applied to its upper surface. This is the style of ice flow observed in most mountain valley glaciers, in the interiors of ice sheets, and in some ice streams. That flow may be enhanced by basal sliding. Where basal drag is small, due to the presence of a weak substrate or high-pressure water, the vertical shearing is also small and the ice moves mainly by sliding and spreading on the lubricating layer. This style of flow is observed in ice streams and in the floating ice shelves that form where glaciers flow to the coast and float on the ocean surface.

Ice Stream Classification

Fast-flowing ice streams are the pathways through which the large ice sheets in Antarctica and Greenland discharge most of the ice accumulated in their interiors. There is considerable evidence that these features were also important parts of the Northern Hemisphere's ice sheets of the Ice Ages. Ice streams today are classified into several types, depending on the physical processes responsible for their fast flow.

Ice streams move tens to hundreds of times faster than the ice sheets through which they flow. Several physical processes responsible for such fast flow have been identified, leading to a range of ice-stream types. Traditionally, the term ice stream was reserved for features unique to the West Antarctic Ice Sheet but it has been expanded to include other very fast-flowing features. The range of ice-stream types lies between two "end members," the ice streams of West Antarctica, for example, Whillans Ice Stream, and the isbrae of Greenland, for example, Jakobshavns Isbrae.

West Antarctic–type ice streams are wide (tens of kilometers) and relatively thin ($\sim$1000 m) features that flow within subtle troughs in the underlying bed topography. They have small surface slopes but flow quickly because weak, water-saturated sediments (called glacial till) within those troughs lubricate the contact between the ice and bedrock. The importance of the weak till is twofold: first, it retards the drainage of basal meltwater, leading to high basal water pressures; and second, water saturation weakens the till, allowing it to deform rapidly as the moving ice pushes over its surface, reducing the basal drag force on the ice. Thus, despite small gravitational driving stresses, West Antarctic–type ice streams flow at speeds of hundreds of meters per year. The gravitational driving stress is taken up primarily by drag in narrow (1000 m or less) "shear margins" at the sides of the ice stream. The flow of the most studied of the these features, Whillans Ice Stream, increases from 200 m per year at its upstream onset to about 600 m per year at its downstream end, where it flows into the adjoining ice shelf.

At the other end of the spectrum, isbrae-type ice streams are narrow ($\sim$10 km) and very thick (1000 to 2000 m or more), with large surface slopes. The resulting large driving stresses yield very rapid ice flow, more than 1000 m per year, in some cases without the benefit of basal sliding. Isbrae are thicker than the surrounding ice sheet because they occupy deep bedrock channels. Isbrae-type ice streams are found in East Antarctica, for example, the Shiraze and Jutulstraumen Glaciers. The large outlet glaciers of the Amundsen Sea Embayment may also be of this type.

West Antarctic Ice Streams

The interior of the West Antarctic Ice Sheet (WAIS) flows slowly over rough bedrock. Downstream, the ice is channeled into a network of fast-flowing tributaries and ice streams, which are separated by slow-flowing ice ridges. While the interstream ridges are frozen to the bed, there is ample meltwater at the interface between an ice stream and its bed. Seismic reflection studies have shown that a soft till layer exists in the shallow troughs beneath many of the WAIS ice streams. This till has been sampled in several locations by drilling through the ice on the Whilans and Kamb Ice Streams and was found to consist largely of marine clays. These clays must have been deposited before the WAIS formed, when the region was an open seaway.

The ice streams of the Ross Sea embayment region of West Antarctica have long been the subjects of intense scientific study because their fast flow may make the ice-sheet system vulnerable to rapid change. As the thick ice sheet flows toward the coast, it eventually thins to the point where buoyancy forces it to float on the ocean surface. The transition between ice resting on bedrock and floating ice is called the grounding line. At the grounding line, the water stored on land in the grounded ice sheet returns to the sea and makes a contribution to sea level. When the balance of ice stored in the ice sheet and ice discharged across the grounding line favors storage, sea level drops. When the balance favors discharge, sea level rises. If the ice streams are capable of rapid changes in discharge rate, the WAIS may be capable of causing rapid changes in sea level.

There is substantial evidence that the Ross ice streams are capable of significant changes in flow rate over time scales of tens to a few hundreds of years. Kamb Ice Stream (KIS) is currently quiescent, discharging ice across the grounding line at a rate of 10 m a^{-1} or less. One hundred fifty years ago it was flowing at more than 350 m per year. The 150-year age for shut-down is measured by the accumulation of snow on the top of cracks that formed on the ice stream surface when it was flowing rapidly. Distortions to internal layers of the ice indicate that the shut-down was rapid, occurring over only a few decades. The cause of KIS shut-down is under investigation and is thought to be related to changes in the water content of the marine clays and in the availability of meltwater at the interface between the ice and clay. Other processes, such as changes in ice stream width, may also be important. The downstream part of Whillans Ice Stream has decelerated at a rate of about 5.5 m per year since the mid-1970s. Together, these changes mean the ice sheet is storing more ice than it is discharging, but it is not yet possible to predict if the trend toward deceleration will continue in the future.

The Weddell Sea sector of the WAIS is drained by ice streams with characteristics that lie between the West Antarctic ice stream and isbrae types described above. Gravitational driving stresses are similar to those in the Ross ice streams but speeds are generally slower. The largest of these ice streams in terms of volume of ice discharge, Rutford and Institute, reach speeds of about 400 m per year at the grounding line. There is no evidence that their flow has been as variable as that of the Ross ice streams.

West Antarctic Isbrae

The WAIS also discharges ice into the Amundsen Sea, predominantly through the Pine Island and Thwaites Glaciers. The characteristics of these ice streams lie near the isbrae end of the range. They flow through deep bedrock channels, have large driving stresses, and attain speeds up to 2500 m per year at their downstream ends. The Amundsen Sea sector is the least studied of the three major regions of the WAIS but the data that do exist indicate that significant change has taken place since the 1970s, inspiring many new research projects. This region is often cited as the most likely to experience large change on human time scales.

Discharge from the Amundsen Sea sector of the WAIS is strongly out of balance, with an estimated 60% more ice lost than gained in recent years. This imbalance is characterized by thinning in the upstream parts of the glaciers and acceleration of flow in the downstream reaches. Velocity of the largest Amundsen ice stream, Pine Island Glacier, has been measured via satellite since the mid-1970s. That monitoring reveals two phases of acceleration, from 1974 to 1987 and 1994 to the present, separated by about 7 years of steady flow. The magnitude of this acceleration, 22% over the entire period, is sufficient to explain thinning inferred from satellite-observed lowering of the glacier surface.

Unlike the Ross and Weddell ice streams, which terminate in large ice shelves, the Amundsen ice stream's grounding lines are close to the open ocean. These marine termini are vulnerable to rapid melting by warming ocean water. The bed beneath Pine Island Glacier slopes down toward the interior of the ice sheet, another possible source of instability; as the grounding line begins to retreat from a steady position, the thicker ice upstream from the old grounding line position floats. Once floating, the ice experiences less basal drag than it did while grounded, and its flow rate will increase. Faster flow will cause the ice to thin, allowing ice still farther upstream to unground. Because the glacier bed deepens upstream, the cycle of floating, accelerating, thinning, and continued ungrounding may not stop. This hypothetical process is often called the marine ice sheet instability. The exact cause of Pine Island and Thwaites Glacier acceleration is not yet known but it is likely that processes acting at the seaward termini of glaciers are important.

East Antarctic Isbrae

A number of large outlet glaciers with thicknesses of more than 1000 m and large driving stresses drain the East Antarctic Ice Sheet. The largest of these is the Lambert Glacier, in the Indian Ocean sector of East Antarctica. Over much of its course, the Lambert Glacier flows at speeds of 400 to 800 m per year. It discharges into the Amery Ice Shelf. Unlike the major isbrae of West Antarctica, the Lambert Glacier is observed to be slowly thickening. Other notable East Antarctic isbrae are the Shirase Glacier, which attains a maximum speed of 2300 m per year, and the Totten Glacier and Ninnis Glacier, both of which attain maximum speeds of about 900 m per year. Overall, East Antarctic isbrae appear to be near steady state, with their seaward fronts both advancing and retreating over the last several decades of observation and new ice accumulation nearly balancing ice discharge.

Antarctic Glaciers

Mountain and outlet glaciers form a relatively small proportion of the ice mass on Antarctica. The majority of these glaciers can be grouped into two categories, those draining ice from the large ice sheets of East and West Antarctica and those on the Antarctic Peninsula. Outlet glaciers move ice through mountain ranges at the edges of the large ice sheets. On the Antarctic Peninsula, ice accumulates in high ice caps and descends toward the coast through mountain valleys.

One of the most unusual environments in Antarctica is the McMurdo Dry Valleys. Most valley floors are glacier free but many small glaciers are found on the ridges flanking the valleys. Most of these glaciers flow only partway down the valley sides, but several, like the Commonwealth and Canada Glaciers in the lower Taylor Valley, extend onto the valley floors. Because the ice is thin and very cold, these glaciers flow slowly due to vertical shearing, at rates of a few meters per year. These glaciers are very old; the Meserve Glacier in Wright Valley has existed for at least 3.4 million years.

The Antarctic Peninsula (AP) is one of the fastest-warming regions on Earth. Along with that warming, its glaciers are also changing. A comprehensive study of glacier terminus locations around the coast of the AP found that 87% of the 244 glaciers mapped have retreated over the last 50 years and that the retreat rate has increased over recent years. Relatively little is known about the thickness and flow of AP glaciers. Where they have been measured, speeds at the grounding lines of large glaciers are on the order of 500 to 1000 m per year. Of particular interest is the response of glaciers that flowed into the Larsen A and B ice shelves on the eastern side of the Peninsula. The Larsen A and B disintegrated in 1995 and 2002, respectively, and since those events, the glaciers that flowed into them have accelerated.

CHRISTINA HULBE

See also **Antarctic Ice Sheet: Definitions and Description; Antarctic Peninsula, Glaciology of; Dry Valleys; Firn Compaction; Ice Ages; Ice Sheet Mass Balance; Ice Shelves; Lambert Glacier/Amery Ice Shelf; Larsen Ice Shelf; Ross Ice Shelf; Thwaites and Pine Island Glacier Basins**

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GLOBAL OCEAN MONITORING PROGRAMS IN THE SOUTHERN OCEAN

In order to be able to respond to the threat of climate change, information is needed about how the climate system works. The ocean stores immense amounts of heat and the greenhouse gas carbon dioxide, and moves both of them slowly around the world, thus influencing climate both regionally and globally. During that slow cycling, ocean waters move through the Southern Ocean, bringing climate signals from elsewhere and taking away the climatic imprint of the Antarctic region. Understanding the role of the Antarctic region in the climate system, as the basis for predicting the timing, magnitude, and direction of future change, therefore requires monitoring the physical properties of the Southern Ocean. That monitoring takes place through the fast-developing Global Ocean Observing System (GOOS), which is the ocean component of the Global Climate Observing System (GCOS).

The GOOS is broadly envisioned to resemble today's global meteorological observation and prediction network: the World Weather Watch (WWW) of the World Meteorological Organisation (WMO). Like the WWW, the GOOS will be supported by national governments and implemented through the contributions of national agencies, organisations, and industries, with the assistance of bodies involved in the national and international management and distribution of data. The development of the GOOS is led by the United Nations through the Intergovernmental Oceanographic Commission (IOC).

The GOOS embraces observations made from ships, buoys, floats, and satellites. The data are fed into advanced numerical models that are capable of producing forecasts of ocean weather and climate. Much of the GOOS is now being implemented through national activities carried out under the umbrella of the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM). This includes programmes that are active in the Southern Ocean as well as elsewhere, such as the following:

1. The Voluntary Observing Ship (VOS) programme, which measures the properties of the upper ocean and the lower atmosphere; a subset of these data is collected to the higher standards required for climate observations, through the climate subset of the VOS, known as VOS-Clim.
2. The Global Sea Level Observing System (GLOSS), which uses tide gauges and the global positioning system (GPS) to measure the height of sea level around Antarctica and its offshore islands, and uses bottom pressure recorders to measure the height of sea level above the deep sea floor in the Southern Ocean.
3. The International Programme for Antarctic Buoys (IPAB), which deploys buoys that drift with the currents at the ocean surface, or on the sea ice, and collects data on the properties of the surface water and lower atmosphere.
4. The Argo float programme, which deploys instrumented floats that move through the ocean at a depth of 2000 m, ascending every 10 days or so to collect a vertical profile of temperature and salinity that is sent back to base via satellite when a float reaches the surface, upon which the float repeats the cycle.
5. The reference buoy network of stations at which measurements are collected of ocean properties through the water column at the same site several times a year to provide a picture of change with time.
6. Observations made of the ocean surface by remote sensing from satellites using instruments of various kinds that can measure changes in ocean surface height (by altimetry), sea-surface temperature (by radiometry), sea-surface roughness (by scatterometry), sea-ice cover (by passive microwave), and ocean colour.

On the global scale, the GOOS was 50% operational in 2005, and is intended to be fully operational by 2010. However, monitoring the Southern Ocean presents a formidable challenge, because it is so geographically remote, such a harsh environment to work in—especially in the southern winter—and so far away from major oceanographic centers and shipping lines. Much more effort than is available at present will be needed to make the GOOS fully operational there. Until that effort is made, the Southern Ocean will represent a gap in the knowledge required to predict climate change accurately.

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See also **Southern Ocean: Climate Change and Variability**

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GONDWANA

Gondwana is one of two giant landmasses that encompassed all the Earth's land areas until about 160 Ma. Gondwana was an amalgamation of what we know today as South America, Africa, Madagascar, India, and Australasia, all grouped around Antarctica. Parts of south and southeast Asia were probably also included. The other supercontinent was Laurasia, made up of North America, Europe, and most of Asia. During the earlier phase of their existence, these two landmasses were in contact and together constituted a supercontinent, known as Pangea. The "Pacific Ocean" was far larger than it is today, and there was a deep oceanic embayment between Laurasia and Gondwana, known as Tethys, which later extended between Europe and Africa and through "Central" America into the eastern Pacific.

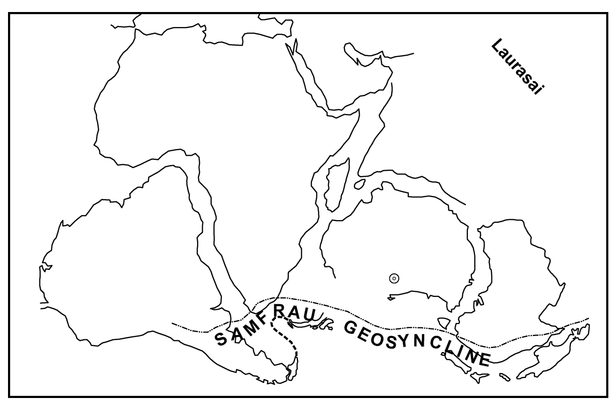
The best early review and argument for the existence of Gondwana is the classic work by Alexander Du Toit (1937). Building upon the theories put forward by the German meteorologist and Arctic researcher Alfred Wegener (1915), Du Toit amassed a wealth of argument for the previous existence of Gondwana. Apart from the obvious geographical argument (notably the jigsaw-puzzle fit of some continents, especially across the Atlantic), there was the geological correspondence of major rock formations across oceans. Furthermore, palaeoclimatological, palaeontological, and biological data for individual continents made much more sense if it were supposed that continents had once been much closer together. From the very outset, Du Toit stressed the vital role of Antarctica, as the key piece in understanding the construction of Gondwana. Later, understanding Antarctica's position would also be crucial to the elucidation of breakup and dispersal mechanisms for marine biota (Thomson and Vaughan 2005).

To many geologists and biologists, the previous existence of Gondwana made a great deal of sense, providing a very neat explanation for the occurrence of similar rock formations and ancient plants and animals in what are now widely disparate landmasses, separated by thousands of miles of deep ocean. A geological map of Gondwana compiled by Campbell Craddock (1970) in the Antarctic Folio, published by the American Geographical Society, drew graphic attention to apparent geological continuities and similarities between Antarctica and other continental pieces of the original Gondwana:

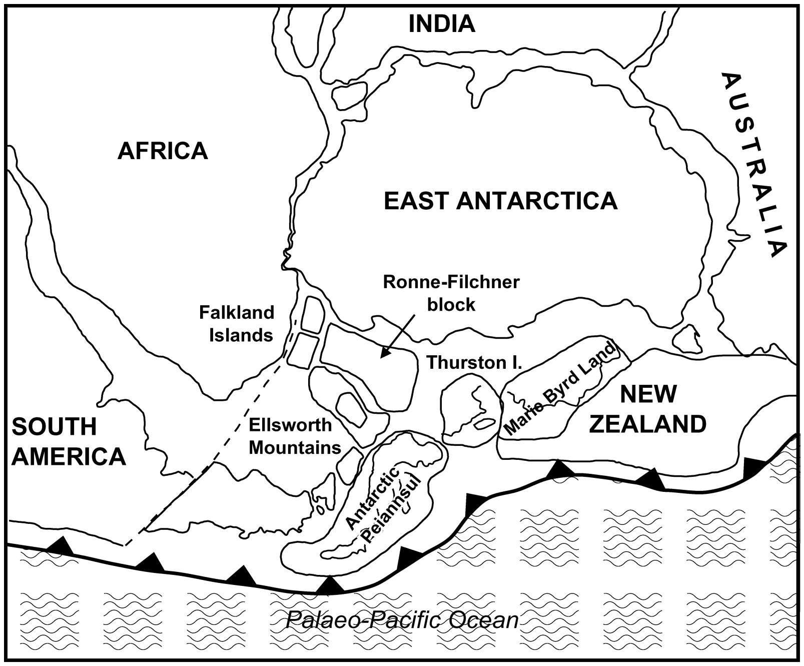
- Cratonic areas of southern Africa, India, East Antarctica, and Australia
- Fold belts of southeastern Australia and northern Victoria Land
- Ellsworth Mountains and the Cape Fold Belt of South Africa
- Antarctic Peninsula and Pacific Marie Byrd Land with South American Andes and New Zealand

These issues were addressed and argued by various authors at the International Symposium on Antarctic Geology and Geophysics in Madison, Wisconsin in 1977, and widely elsewhere. They have also formed the focus of several international, intercontinental geological field studies.

In the upper Palaeozoic and lowest Mesozoic (Trias) sequences of South America, southern Africa, Madagascar, India, Australia, and Antarctica there is a basic stratigraphical succession that, whilst not everywhere identical, nevertheless shows a remarkable



Reconstruction of Gondwana in the Palaeozoic, simplified and redrawn from DuToit (1937). After many years of argument, the basic pattern has changed remarkably little, apart from our more detailed understanding of complexities on the palaeo-Pacific margin. We now know that DuToit's SAMFRAU (South America, South Africa, and Australia) geosyncline includes rocks of ages other than Palaeozoic. His reconstruction is distorted, principally because he maintained a link between South America and the Antarctic Peninsula via the Scotia arc (a Cenozoic structure).



Modern reconstruction of Gondwana for the early Jurassic (about 190 Ma) showing the palaeo-Pacific margin as a jigsaw of continental fragments. In particular, note the position of the Falkland Islands. The area that is now the Weddell Sea is almost entirely occupied by the Ellsworth Mountain and Ronne-Filchner blocks. The toothed line represents a subducting margin to the palaeo-Pacific Ocean. (Simplified from Thomson and Vaughan 2005, fig. 14.)

degree of commonality. Key units are a Carboniferous–Lower Permian glacial sequence (commonly resting on an erosion surface), Permian sedimentary rocks with a *Glossopteris* flora (e.g., Plumstead 1962) and locally well-developed coals, and a Triassic terrestrial sequence with floras characterized by *Thinnfeldia/Dicroidium* and with similar amphibian and reptilian vertebrate faunas (e.g., Colbert 1982).

Sequences of Late Carboniferous and Permian glacial deposits (about 338–256 Ma) locally resting on scratched pavements are found in Brazil and Argentina, southern Africa, the Indian subcontinent, the Malaysian region, Australia, and Antarctica. Plotted on a modern map of the world, the occurrences make little sense; they are not only widely dispersed, but many occur in areas that today experience tropical climates. Plotted on a map of Gondwana, however, they come together as the vestiges of one glaciation, centred more or less on Antarctica, with ice sheets radiating out into once-contiguous landmasses. The distribution of the postglacial Permian *Glossopteris* flora in the rocks of South America, southern Africa, Madagascar, India, Australasia, Antarctica, and even Anatolia also makes more sense if it is viewed as a Gondwanan vegetation (which also achieved some incursion into southern Laurasia). Whilst critics might argue that plants may achieve distribution by wind or sea, the distances involved are huge. For land animals, the problem of dispersal is even greater and contiguous land is a prerequisite for almost all. Thus the discovery of a varied Triassic vertebrate fauna of amphibians and reptiles (typified by the reptile *Lystrosaurus*) in the Transantarctic Mountains, many of which were known also from South Africa and India, but unlikely candidates for transoceanic migrations, provided a clinching argument for the existence of Gondwana for most palaeobiologists.

Nevertheless, however attractive it may have been to some, the concept of Gondwana came in for stiff criticism, not least from those who were unable to find a mechanism for the subsequent breakup and dispersal of the supercontinent (Le Grand 1988). It also posed headaches for believers. Reconstructions that otherwise satisfied the known geological constraints of the day all too often ended up with the Antarctic Peninsula overlapping southern South America or the Falkland Plateau, and the Ellsworth Mountains of Antarctica with their typical Gondwanan geology set at an anomalous structural angle to related sequences in the Transantarctic Mountains. Madagascar oscillated between a position tucked in south of the horn of Africa and an alternate location tucked into the coastal embayment of Mozambique.

The dilemma of the Antarctic Peninsula was encapsulated in a paper by Ian Dalziel and David

Elliot (1982), but help was at hand if Antarctica was not viewed as a rigid entity through geological time. The concept of West and East Antarctica as separate tectonic units, and the west made up of several discrete microcontinental blocks, each with its own movement history, made it possible to solve the Gondwana puzzle in terms of all external constraints without the embarrassing inconveniences of overlaps and strange tectonic orientations. It even turned out that the Falkland Islands came from somewhere adjacent to Natal and had been rotated by approximately 180° in the process (Curtis and Hyam 1998). Likewise, the Ellsworth Mountains are now generally believed to have rotated counterclockwise from a position closer to the Weddell Sea coast of East Antarctica. Currently favoured reconstructions of Gondwana depict the peninsula lying west of southern Chile, and West Antarctica a compact mass of fragments that have very different relative positions today.

As important as the previous existence of Gondwana are the mechanism of its breakup and the dispersal history of the ensuing fragments. Breakup began about 180 Ma in the area between the southeastern margin of Africa and northwestern Dronning Maud Land, probably when heating and doming of the crust in response to a hot plume of molten rock rising from the mantle caused the crust first to fracture and then to spread apart (Storey 1995). From about 165 Ma, the region between the two became an expanding ocean with arms radiating out to become the South Atlantic and the Indian oceans. Freed of its attachment to Antarctica, India moved rapidly northward to collide with Asia, forming the Himalayan chain in the collision zone. The last remaining connections between Antarctica and fragments of old Gondwana were those between the Antarctic Peninsula and southern South America, and between Australia and northern Victoria Land. Severance of these two land connections 32.5 and 31 Ma, respectively, broke down barriers to marine connections and made possible the development of a deep-water Antarctic Circumpolar Current (Thomson 2004), which isolated the continent physically and climatologically.

Yet, even as Gondwana was breaking up, it still had an important role to play in the distribution of terrestrial plants and animals. The southern beech, today restricted to southern South America and Australasia, is known as fossils from the late Cretaceous of Antarctica (approximately 75 Ma) but not at all from South Africa or India. It thus seems that these plants developed after Africa and India had separated from their Gondwana neighbours. Widespread throughout the Americas in the geological past and probably originating from there in the late Cretaceous, marsupial, or pouched, mammals are today best known from Australia, with a fossil record that extends back to the late Oligocene. They are, however, unknown from Africa, India, and even New Zealand, all of which had separated from the rest of Gondwana in the Late Jurassic and mid Cretaceous. It thus appears that the previous existence of Gondwana can best explain the distribution of plants and animals in our world today and that Antarctica played a key role as a migration path.

Michael R. A. Thomson

See also **Antarctic Peninsula, Geology of; Circumpolar Current, Antarctic; East Antarctic Shield; Fossils, Plant; Fossils, Vertebrate; Geological Evolution and Structure of Antarctica; Plate Tectonics; Transantarctic Mountains, Geology of**

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GOUGH ISLAND

Gough Island has been described as the most important seabird island in the world. It lies in the mid South Atlantic at 40°21′ S, 9°53′ W and forms part of the United Kingdom Overseas Territory of Tristan da Cunha. The island was discovered in 1505 by Portuguese sailors, although an 1804 visit by a sealing gang was the first confirmed landing.

Gough Island covers 6400 ha and is roughly rectangular in shape. It is a volcanic island, about three million years old, with the last eruption occurring 130,000 years ago. The island is mountainous with steep coastal cliffs. With the exception of a low-lying area in the south, the land rises steeply to a central plateau above 500 m, with the highest point, Edinburgh Peak, at 910 m. There are numerous offshore islets and rocks within 1 km of the island. Gough's climate is cold-temperate, with strong prevailing westerly winds, a mean annual precipitation of 3154 mm, and a mean monthly temperature between 8.9°C in August and 14.5°C in February. Snow can fall in the interior, but rarely at sea level.

In 1976 Gough Island and its territorial waters out to three nautical miles were declared a wildlife reserve. A management plan was adopted in 1993. In 1997 the island was renamed the Gough Island Nature Reserve and its boundaries extended out to 12 nautical miles. Gough Island and its territorial waters were designated a World Heritage Natural Site in 1995. Another island in the Tristan da Cunha Group, Inaccessible, was added to form the Gough and Inaccessible Islands World Heritage Site in 2004.

Gough supports an altitudinal succession of vegetation types, from coastal tussock grassland through to lowland fernbush, up to an altitude of 500 m, where highland vegetation of wet heath, peat bog, feldmark, and montane rock communities occur. The flora on Gough Island is typical of southern cold-temperate oceanic islands, with relatively low species diversity, and a predominance of ferns, lichens, and bryophytes, although two tree species occur. Currently, 281 plant species are recognized on Gough, of which 12 are endemic and 24 introduced. The range of most alien plants is limited to disturbed areas and only four species are widespread.

The indigenous invertebrate fauna is characterized by relatively low species diversity, typical of Southern Ocean islands. Over 100 free-living species have been recorded, but due to inadequate sampling and taxonomic study of many taxa, the true number of species is likely to be much greater. There is a large number of introduced invertebrates.

There are twenty breeding seabird species totalling millions of pairs (mainly members of the Procellariiformes—albatrosses and petrels) and two endemic land bird species (the flightless Gough moorhen *Gallinula comeri* and the Gough bunting *Rowettia goughensis*). The seabirds play an important role in the island's terrestrial ecology through the importation of large quantities of marine-derived nutrients, mainly in the form of guano. Virtually the entire world population of the endangered Tristan albatross *Diomedea dabbenena* and the vulnerable Atlantic petrel *Pterodroma incerta* breed on Gough Island. Also breeding is the world's largest population of the endangered sooty albatross *Phoebetria fusca,* second-largest population of the endangered Atlantic yellow-nosed albatross *Thalassarche chlororhynchos,* over 100,000 pairs of the vulnerable rockhopper penguin *Eudyptes chrysocome,* and millions of burrowing petrels, notably the great shearwater *Puffinus gravis*.

Two native mammal species breed on the island, the sub-Antarctic fur seal *Arctocephalus tropicalis* and the southern elephant seal *Mirounga leonina*. Both species were hunted extensively during the nineteenth century and almost driven to local extinction. Only the fur seals have since recovered, and currently some 200,000 are found on the island. The elephant seal population remains small with only ten to fifteen pups born each year.

The only alien mammal currently occurring on Gough Island is the house mouse *Mus musculus,* likely to have been accidentally introduced by sealers, sometime in the early nineteenth century. Mice are now ubiquitous on the island, with densities reaching at least 224 individuals/ha. They have evolved a larger body size than elsewhere, perhaps due to a combination of reduced temperature, extended longevity, and low predation, together with a high energetic content of food, especially avian material.

The inshore waters of Gough support a fishery for the Tristan rock lobster *Jasus tristani*. The marine life is little known, although a number of species of fish occur in abundance within the surrounding kelp beds. Southern right whales *Eubalaena australis* occasionally visit.

The South African Weather Service and the South African National Antarctic Programme (SANAP) of the Department of Environment Affairs and Tourism have maintained a small meteorological station on

Gough Island under agreement with the Tristan Government since 1956. Located on the coastal cliff above Transvaal Bay, it is the island's only standing human construction. The station supports an annually rotated staff of at least six people.

There has been considerable scientific interest in the islands since the late 1700s. The Gough Island Scientific Survey undertook the first multidisciplinary study of Gough Island over a period of 6 months in 1955/1956. It conducted inventories of the island's fauna and flora, as well as studies of its geology and palaeontology, and produced the first map. More recently there have been multiyear investigations of the island's fauna (invertebrates, threatened birds, and the introduced mouse), conducted by both South African and United Kingdom scientists.

Unexpectedly, in the first few years of the new millennium it was discovered that the house mouse was preying upon chicks of the winter-breeding Tristan albatross and Atlantic petrel, literally eating them alive over a period of several nights. Modelling the birds' consequently lowered breeding success suggests that both species are at risk of extirpation (the albatross also being adversely affected by fishery-related mortality while at sea). Research is now being conducted to assess how the mice can be eradicated, most probably by dropping poison bait from helicopters over the whole island in a single operation. Such an exercise, whereas theoretically feasible, will be hugely expensive and thus a test of political will to fund.

John Cooper

See also **Albatrosses: Overview; Antarctic Petrel; Petrels: Pterodroma and Procellaria; South Africa: Antarctic Program; Southern Elephant Seal; Southern Right Whale; Sub-Antarctic Fur Seal; Yellow-Nosed Albatross**

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GREENPEACE

Greenpeace is a nonprofit international environmental organization. Greenpeace's trademark tactics combine nonviolent direct action and "bearing witness"—a form of active–passive resistance originated in the Quaker traditions of some of the organization's earlier activists, which involves protesting injustices by being present to observe them. Greenpeace used these approaches to bring the plight of the Antarctic region to the public's attention, and to promote its protection as a wilderness region, in particular through opposing mining, whaling, and unsustainable fishing.

Greenpeace was founded in Vancouver, Canada, in 1971. A broad range of people converged in Vancouver at the time—hippies, peaceniks, radical ecologists, Quakers, Vietnam War draft dodgers. Vancouver was also the largest city closest to Amchitka Island in the Aleutians, where the US Atomic Energy Commission was planning to conduct a 5-megaton nuclear weapon test, the largest in US military history. The testing program generated concerns about the effect of underground nuclear explosions in a seismically active area, and substantial public opposition. The "Don't Make a Wave Committee" was created to oppose the testing, and some of its members attempted to reach the test grounds in a wooden halibut fishing boat, the *Phyllis Cormack,* to "bear witness"—and to report back. This committee later became Greenpeace, a combination of words—coined by Bill Darnell—that links concern for the earth and opposition to nuclear arms. Robert Hunter created the concept of reaching to public consciousness through dramatic images of environmental abuse—what was called the "Media Mind Bomb." David McTaggart, who in 1972 led Greenpeace's second protest voyage to oppose French nuclear testing in the South Pacific, convinced several loosely connected groups to form Greenpeace International in 1979 (Brown and May 1989).

It was McTaggart who directed the attention of Greenpeace to Antarctica. In 1978 Jim Barnes had set up the Antarctic and Southern Ocean Coalition (ASOC) as an international coalition to protect Antarctica, and he persuaded McTaggart that

Greenpeace should support the World Park Antarctica campaign. The World Park concept was based on the protection of the Antarctic wilderness values and wildlife; and in the maintenance of Antarctica as a zone of peace, free of all weapons, and devoted to international scientific cooperation. The exact legal form of the concept was not spelt out—it could be enacted through existing legal entities such as the Antarctic Treaty System, or through the mechanisms of the World Heritage Convention (Brown and May 1989).

The initiation of negotiations by the Antarctic Treaty States for a convention to open the continent for minerals exploitation was the trigger for Greenpeace's involvement, which began in 1983. Initially, the Antarctic campaign involved working to enhance the efforts of ASOC, and lobbying at Antarctic Treaty meetings and at the wider community of states in the United Nations (whose General Assembly discussed annually the "question of Antarctica"). Greenpeace conducted protests in the capital cities of Antarctic Treaty Parties, and delayed the departure of vessels leaving to Antarctica to conduct oil research. Later, Greenpeace took its protest to Antarctica itself to further increase pressure on Antarctic Treaty Parties (Brown and May 1989; Rigg 1995).

The first Greenpeace Antarctic expedition, in 1985–1986, departed from Lyttelton, New Zealand, intending to build a base at Ross Island. Operating a base would provide Greenpeace with direct Antarctic experience and thus the capacity to speak with credibility with Antarctic Treaty Parties. However, ice conditions prevented the expedition from reaching its destination. The base was built and tested in New Zealand during the austral winter, and Greenpeace tried again the following summer, anchoring off Cape Evans on January 25, 1987. By February 13 the base—a prefabricated green hut—had been completed. World Park Base (77°38′ S, 166°24′ E) was located 200 yards to the northeast of the hut from Robert Falcon Scott's last expedition, at a site previously occupied by the base camp of a private expedition. Its purpose was to monitor human activities in the surrounding area (particularly McMurdo Station, 18 miles away); carry out a modest program of scientific research; and draw public attention to the future of the continent, in particular to generate opposition to the minerals convention. World Park Base operated year-round with a crew of four (both men and women) and was supplied annually by Greenpeace ships. World Park Base pioneered environmentally friendly approaches to Antarctic operations—such as the removal of all waste and the use of alternative energy (Brown and May 1989; Greenpeace 1994; Roura 2004).

Other Greenpeace Antarctic Expedition actions included blocking temporarily the construction of an airstrip at the French base Dumont D'Urville (of particular concern because it involved dynamiting several small islands rich in bird life); and protesting poor waste and fuel management practices—for instance, by depositing trash from McMurdo's dump at the station's administration building. In the Southern Ocean, Greenpeace disrupted the "scientific" killing of minke whales and unsustainable fishing activities. From 1987–1988 Greenpeace began conducting unofficial review visits to Antarctic stations, focusing on their environmental performance. (The reception for Greenpeace activists during these "inspections" ranged from being invited to lunch to being assigned an unwanted military escort.) Between 1987–1988 and 2001 Greenpeace visited, and reported on, over 160 sites or facilities, mostly in the Antarctic Peninsula and Victoria Land (ASOC & UNEP 2003).

Action on the ice and in the Southern Ocean was tightly coupled with media work, political lobbying, and technical engagement in specialized fora—with feedback both ways, and through the ASOC network. Images from Greenpeace's direct actions went around the world, and documentation from the expeditions was provided to Antarctic Treaty Consultative Meetings, meetings of the Convention for the Conservation of Antarctic Marine Living Resources, or the International Whaling Commission.

Greenpeace's methods were criticized as "confrontational" by some of the targets of its activism (e.g., Browne 1990). Some have speculated that there exist links between the high-profile public campaign for the protection of the Antarctic and the growth of Antarctic tourism (e.g., Hemmings 1997).

Following NGO efforts, Australia and France rejected the minerals convention, CRAMRA, and as more nations also decided not to ratify the convention, it was ultimately abandoned in favor of the 1991 Protocol on Environmental Protection to the Antarctic Treaty, with its 50-year moratorium on mineral resource activities. World Park Base was entirely removed in 1991–1992, after the signature of the Protocol. The removal included environmental remediation, and a monitoring program that lasted until 1995–1996 (Roura 2004). Between 1991 and 1998 Greenpeace lobbied in most Antarctic Treaty states and internationally for the ratification and implementation of the Protocol. In the mid-1990s, Greenpeace began to focus on the impacts on the Antarctic environment resulting from global (rather than local) activities, and began documenting the emerging effects of climate change in the region (Dalziell 1996), such as the collapse of the Larsen Ice Shelf. Since the late 1990s Greenpeace has been focusing on the increasing threat of Southern Ocean fishery collapse, in response to illegal, unregulated, and unreported fishing.

Greenpeace's Antarctic campaign helped to generate public interest in the protection of Antarctica, which in turn catalyzed changes in Antarctic policy on the part of the Antarctic Treaty nations. Consequently, environmental protection became one of the pillars of the Antarctic Treaty System (e.g., Bastmeijer 2003). Greenpeace's Antarctic presence strengthened the case for environmental NGOs gaining expert status at the Antarctic Treaty Consultative Meetings, which ASOC was granted in 1991. (Before then, the meetings were conducted behind closed doors, and activists could only gain access to delegates at coffee breaks. However, a parallel application for expert status by Greenpeace itself was rejected.) Greenpeace claims as a victory the establishment of the Southern Ocean Whale Sanctuary, approved by the International Whaling Commission in 1994. Greenpeace's support for Antarctic research resulted in several publications in peer-reviewed scientific journals.

At its peak the Antarctic campaign costs reached several million US dollars annually. Greenpeace funds its activities primarily with the voluntary donations of individual supporters, supplemented with grant support from foundations. Its funding policy is designed to ensure complete independence from all governments, corporations, and political parties. Presently Greenpeace, whose international headquarters are in Amsterdam, The Netherlands, has a presence in forty countries across the Americas, Asia, Europe, and the Pacific, and a fleet of ships that includes two ice-class vessels. Some of Greenpeace's current campaigns, including campaigns to stop climate change, stop whaling, and save the oceans, involve activities in the Antarctic Treaty Area and adjacent regions—as well as in the Arctic.

RICARDO ROURA

See also **Antarctic and Southern Ocean Coalition (ASOC); Antarctic Peninsula; Antarctic Treaty System; British Antarctic *(Terra Nova)* Expedition (1910–1913); Climate Change; Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Convention on the Regulation of Antarctic Mineral Resource Activities (CRAMRA); Fisheries and Management; International Whaling Commission (IWC); Larsen Ice Shelf; McMurdo Station; Minke Whale (Antarctic Minke Whale); Protocol on Environmental Protection to the Antarctic Treaty; Ross Island; United Nations**

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GREY-HEADED ALBATROSS

The grey-headed albatross *(Thalassarche chrysostoma)* is a medium-sized albatross weighing between 3 and 5 kg, with a wingspan of over 2 m. Adults are distinguished by a combination of a grey head with a white crescent just behind the eye, a black bill with narrow, bright yellow ridges, and a mostly white underwing with a broad black leading edge.

Grey-headed albatrosses are a globally threatened species classified as vulnerable because of an estimated decrease of 48% over 3 generations (90 years). If the major population decreases observed at some sites are shown to be occurring elsewhere in the species range, it is projected that the conservation status of the species will be relisted as endangered.

Grey-headed albatrosses breed in Chile and at six sub-Antarctic island groups in the Southern Ocean. The annual breeding population is estimated to be 92,300 pairs, equivalent to a total of about 250,000 mature individuals. The population at South Georgia is the largest across the species range and accounts for 56% of the global population. Other large populations occur at Isla Diego Ramirez in Chile, Marion and Prince Edward Islands, the Campbell Islands, and a small population on Macquarie Island.

Grey-headed albatrosses are essentially biennial breeders with a breeding season that extends over 8 months. They typically breed on tussock slopes and cliff terraces, sometimes in association with other albatross species. Breeding adults return to the colonies in early September to early October with males returning about a week ahead of the females. Both adults share the 10-week incubation period, the eggs hatching in December and early January. The chicks are brooded for 3 to 4 weeks after hatching, and chicks fledge at about 20 weeks of age. Typically successful breeders depart the colonies when chicks fledge in late April and May.

Juvenile grey-headed albatrosses generally return to their breeding island when they are 6 to 7 years of age, and breed when 10 to 14 years. The life history of grey-headed albatrosses is well studied at South Georgia, where, over the last 2 decades, the Bird Island population has decreased at an annual rate of 1.4%–1.8%. This population decrease is mainly a result of decreases in juvenile survival rate (from 35% to 5% recruitment) and reduced survival rates of adults (95% to 93%).

Grey-headed albatrosses have an oceanic distribution and are found in sub-Antarctic and Antarctic waters between 46° and 64° S during summers and between 39° and 51° S during the winter months. Satellite tracking of breeding adults from South Georgia showed regular use of core feeding areas in the Antarctic Polar Frontal Zone (APFZ), which is likely an area of predicable aggregations of prey associated with mesoscale oceanographic features. Breeding birds also make extensive use of shelf waters, the reliance of different feeding habitats varying among years. During the 18-month nonbreeding-period season, grey-headed albatrosses from South Georgia undertake a circumpolar migration, one bird recorded as completing the trip in just 46 days. Grey-headed albatrosses have distinct migration strategies, with some individuals exploiting the same key staging areas in successive winters.

Grey-headed albatrosses obtain their prey by surface seizing, and also by diving to depths of 6 m. Most foraging occurs during daylight hours, and a combination of squid, fish, and krill is most commonly consumed, the relative proportions of prey varying with foraging habitat. Grey-headed albatrosses also scavenge offal and discards from fishing boats, and as a result they are vulnerable to being hooked and drowned on longlines as they scavenge on the baited lines. Mortality of grey-headed albatrosses in longline fisheries has been identified as a major cause of the population decrease. In the absence of adoption of effective changes to fishing practices it is projected that such decreases will continue into the future.

ROSEMARY GALES

See also **Albatrosses: Overview; Antarctic Important Bird Areas; Campbell Islands; Macquarie Island; Prince Edward Islands; Seabird Conservation; Seabird Populations and Trends; Seabirds at Sea; South Georgia**

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GROWTH

Growth in Antarctic marine cold-blooded species is slow. This has been known for more than 25 years. Generally, growth rates are slowed by around two to five times compared to temperate species. A few studies have reported fast growth in Antarctica for some sponges (Dayton et al. 1974), ascidians (Rauschert 1991), and bryozoans (Barnes 1995). However, the fast rates here are only as fast as slow rates elsewhere, and when the whole range of growth is viewed, it is generally depressed at high latitudes. A typical example is the brachiopod *Liothyrella uva,* which takes around 50 years to reach maximum size. This was verified by linking enhanced ^{14}C levels in shells to periods of increased ^{14}C following nuclear bomb tests (Peck and Brey 1996). Growth is often estimated from growth rings, and these, too, show great age in Antarctic species. Seasonal variations in isotopes in shells have also been used to show that rings are laid down annually in the bivalve *L. elliptica* (Brey and Mackensen 1997).

Studies showing faster growth rates in some species, along with relatively fast summer growth in pelagic invertebrates, have been used to argue that low temperature itself cannot constrain growth, and that growth is limited by seasonally restricted food supplies. This argument still continues, with some species exhibiting highly seasonal periods of growth (e.g., the urchin *S. neumayeri*) (Brockington 2001), whereas others that feed seasonally appear to grow more evenly throughout the year (e.g., the bivalve *Y. eightsi*) (Peck et al. 2000). Both of these have been viewed as supporting seasonal growth limitation, the former through cessation of growth in winter, and the latter through the spreading of growth effort through the year to optimise efficiency of use of stored reserves. Some studies have shown slow growth in the presence of unlimited food resources in adults (e.g., the amphipod *Waldeckia obesa,* which might live to 8 years). However, possibly the best support for temperature limitation of growth comes through analyses of larval development, where Hoegh-Guldberg and Pearse (1995) showed that development in feeding and nonfeeding larval types was similarly slowed at low temperatures. It is also interesting that development in protected embryonic forms is markedly slowed in Antarctic species, which has been well demonstrated in molluscs (Hain 1991) and amphipods (Sainte Marie 1991). Both temperature and seasonality probably place restrictions on growth in different parts of the life cycle.

There is recent evidence showing that proteins may be less stable and more difficult to synthesise at low temperatures (Fraser et al. 2002). This is one mechanism where low temperature might limit growth.

Slow growth at polar latitudes comes with extended lifetimes and deferred maturity. Where studies exist, all show extended longevity in Antarctic species. Thus, Antarctic sea urchins, brachiopods, and bivalve molluscs all live for more than 50 years, and the starfish *O. validus* has been estimated to live more than 100 years. Data for sponges is even more extreme, with some age estimates for Antarctic species in the hundreds, and possibly in excess of 1000 years (Gatti 2002). Cold-water species also exhibit deferred maturity. They do not begin to reproduce until much later than warmer-water relatives, and their rates of gamete maturation also take much longer than warmer-water species. All of these slowed biological rates are likely to make Antarctic marine species vulnerable in a changing environment, because their responses will be slower than lower-latitude relatives.

LLOYD PECK and GAUTHIER CHAPELLE

See also **Benthic Communities in the Southern Ocean; Molluscs**

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H

HANSSEN, HELMER

Helmer Julius Hanssen participated on Roald Amundsen's first three polar expeditions and was in the five-man group that reached the South Pole on December 14, 1911.

Helmer Hanssen was born in Andøy, northern Norway, on September 24, 1870, and followed a traditional pattern of farm work and fishing from an early age. Small whale and seal hunting in the Arctic, his certificate as ship's mate, and participation on Henry J. Pearson's expedition to Novaya Zemlya in 1897 gave him a good foundation for polar expedition work. When Pearson's expedition was about to start from Sandefjord in Norway, Hanssen met Roald Amundsen, who was preparing to leave with the Belgian Antarctic Expedition in *Belgica*. After more years as a sealer and ship's mate, Hanssen joined Amundsen's *Gjøa* expedition through the Northwest Passage, 1903–1906, after being recommended by a mutual acquaintance. Thereafter followed an 18-year-long association with Amundsen. On the *Gjøa* expedition Hanssen learned dogsled driving, which was to be his particular expertise on the South Pole expedition.

After *Gjøa*'s return, Hanssen worked as a customs officer in Tromsø, northern Norway, but was given leave to participate on the Amundsen expedition that went to the Antarctic in 1910–1912. With his skill at dog-driving, he was a natural choice for the Pole party, and he drove the leading sledge the entire way, except for the very last part, when he let Amundsen ski in front to be the first to reach the Pole. Hanssen's experience regarding dogs, sledge travel, clothing, igloo building, and food on long journeys had been acquired in close contact with the Inuit on King William Island during the *Gjøa* expedition, but he seems also to have had a natural talent for work with dogs, and he boasted that he almost never had to use the whip. Without a doubt, he was a key person on the South Pole expedition, and he contributed greatly to the success of the sledge journey.

Hanssen participated as skipper on Amundsen's next expedition, in *Maud* through the Northeast Passage, 1918–1920, but his relationship with Amundsen turned sour during this frustrating, ice-struck voyage, and he was dismissed when *Maud* reached Nome, Alaska. During the last winter on board, Hanssen had made a rigorous sledging journey for Amundsen from the expedition's winter harbour at Ayon Island to the nearest functioning telegraph station at Anadyr by the Bering Strait and back, a distance of c. 4000 km that took six and a half months. After his dismissal in Nome, Hanssen had to take work in industrial gold digging to earn money for his ticket home.

Hanssen participated as dog driver on the Oxford University Spitsbergen Expedition in 1924 and crossed Nordaustlandet with the expedition leader George Binney. In 1926 he assisted a German film expedition in Svalbard and Northeast Greenland. On this trip he met the American polar explorer Richard E. Byrd, but declined to join him on a new Antarctic expedition. The rest of his working life was spent in Tromsø, where he died on August 2, 1956.

Susan Barr

See also **Amundsen, Roald; Norwegian *(Fram)* Expedition (1910–1912); Wisting, Oscar**

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HEALTH CARE AND MEDICINE

No Antarctic-specific ailment or disease has been diagnosed. Humans going south are transient visitors and, as many are highly mobile, diseases contracted in tropical or temperate areas may occur in Antarctica, consistent with the age and sex of the individual. Health care is therefore the practice of medicine in Antarctica, as varied as that practice is, and not a specialty of Antarctic-specific disease states.

Each group, whether national research, tourist, or adventure seeking, has assessed the risks and developed health care in response to the perceived needs. Multidisciplinary medical teams and elaborate medical suites and equipment contrast with no medical staff and basic materiel. National programs have chosen different models, civilian, military, contract, or, within the national organization, a combination of these. Determining factors include the degree of physical isolation, medical logistics capabilities (especially the ability to provide medevac by ship or aircraft), and the number and skills of the medically trained staff. Traditional tourist vessels with older passengers have different needs from those catering to the younger, more adventurous visitors.

As a number of wintering Antarctic medical services have an evidence base of decades, operating with no prospect of timely evacuation, preventive medicine has become the cornerstone of the service. Judicious planning has seen the assessment of the risk–benefit of every potential procedure, with a service that is not unrealistic in what should be provided or the ultimate outcome. Preventive principles are reflected in predeparture medical screenings including psychological and/or psychiatric assessment, training of medical staff, first-aid training for all personnel, medical and first-aid manuals, and prophylactic appendectomy for the physician. Screening was performed by a number of expeditions in the Heroic Era. Guidelines for such were and are variable, ranging from disqualification of candidates for specific conditions such as diabetes, asthma, and heart disease, to the granting of waivers. Physical examinations vary, but generally include laboratory investigations, electrocardiogram, chest x-ray, and blood-donor screening.

Contrary to popular belief, the environmental conditions of cold injury, hypothermia, and snow blindness are uncommon; most are experienced in accidents and recreational pursuits such as skiing and driving snowmobiles. Increased ultraviolet radiation, as a consequence of ozone depletion, has not been found to be a problem, as polar clothing covers most of the body and sunscreens and goggles are universally used.

Trauma and accidents are common, with most of a minor nature. Injuries range from lacerations, abrasions, musculoskeletal sprains and strains, and burns, to fractures and multiple trauma. Ill-defined conditions such as headaches, dyspepsia, and insomnia, endemic during the 24 hours of summer daylight, occur frequently. Dental and skin problems are also common. The latter may be *polar hands,* the presence of painful cracks in the skin of fingers, especially around nails, caused by the dry, cold environment. Diagnoses made and treated in Antarctica include appendicitis, breast, lung, and testicular cancer, gall bladder disease, gout, heart attack, hepatitis, intracranial bleeding, kidney stones, malaria, peptic ulcer, pneumonia, amoebic dysentery, scurvy, hypervitaminosis A, and mental and behavioral disorders.

Over a thousand persons have died in Antarctica, but the mortality rate is low when compared with more densely populated regions. The majority perished in two disasters. In September 1819 the Spanish warship *San Telmo* was wrecked on Livingston Island, drowning hundreds of officers, crew, and military personnel. A crash of an Air New Zealand flight into Mount Erebus killed 257 tourists in November 1979. Deaths in the Heroic Era contrast with recent fatalities: three skydivers, a young woman on a yacht from complications of diabetes, and a number of tourists from heart attacks. Deaths on national expeditions have resulted from carbon monoxide poisoning, burns, falls into crevasses, drowning, multiple trauma, hypothermia, alcohol poisoning, cerebral hemorrhage, perforated gastric ulcer, appendicitis, and heart attacks.

The medical armamentarium has evolved over the past century from simple chests to the best now having suites complete with library, examination, emergency, sterilizing, laboratory, and diagnostic equipment, patient ward, operating theater with surgical, anesthetic, orthopedic, obstetric, and dental instruments and equipment, and an extensive range of pharmaceuticals. Procedures have ranged from removal of a splinter to brain surgery.

Since the introduction of the wireless to Antarctica, medical communications have been important, from station physician to consultants outside Antarctica and to scientists in the field, where facilities and equipment are primitive. Telemedicine has been practiced in Antarctica for 40 years. Improvements have come with modern technology and the advent of satellite communications, not subject to radio *black-outs*. Data, clinical and pathology photographs taken through a microscope, x-rays, ultrasound images, and electrocardiograms are routinely sent to consultants outside Antarctica. Many doctors have access to phone, fax, e-mail, data circuits, and the World Wide Web. In addition to providing clinical and peer support, telemedicine and medical informatics provide continuing medical education, access to databases, electronic patient records, electronic journals, and inventories to remote medical staff.

Polar medicine has always had a close nexus with human biological research. International collaboration over 50 years in research, sharing diagnostic dilemmas within a SCAR medical working group, and in medevacs, together with recent initiatives within COMNAP, have improved standards of care in Antarctica. Community attitudes as well as the expectations of groups isolated on the Antarctic Continent and of their families and friends at home have also played a part, but it is unrealistic to expect the standard to be that of the world's best practice. Although highly qualified doctors have provided excellent cover, provision of a continuing service has been hampered by lack of physicians with the necessary personality and skill set to deal with the demands of practice with its isolation, confinement, and separation from colleagues. Many ethical and medico-legal issues face those providing health care. Availability of equipment and supplies, skills of staff, privacy and confidentiality, medical indemnity, status of walking blood banks, and who doctors the doctor are but a few. A physician removed his own appendix in 1961, and there have been highly publicized evacuations of doctors from the continent in the past 10 years. Many of these issues face those organizing medical services for long-duration space expeditions, Antarctica being an ideal analogue for space medicine.

Antarctica being central to research on global climate change, a much-sought-after tourist destination, and an important analogue for space, Antarctic health care and medicine continue to evolve.

DESMOND J. LUGG

See also **Living in a Cold Climate**

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HEARD ISLAND AND McDONALD ISLANDS

Heard Island is located at 53°05′ S, 73°30′ E in the southwest Indian Ocean, approximately 4350 km southwest of Australia, 4850 km southeast of South Africa, and 1650 km north of the Antarctic continent. Heard Island is broadly circular in shape, approximately 40 km east–west and 20 km north–south, and dominated by Big Ben, an active volcano of 2745 m elevation and radiating buttresses. Heard Island lies south of the Antarctic Polar Front (formerly known as the Antarctic Convergence) and 70% of the island is permanently covered in glaciers. This permanent ice cover has decreased from 79% in 1947, and is continuing.

The island has a relatively narrow coastal area, with ice-free headlands flanked by glaciers around the coastline. There are numerous rivers and streams on the island, fed by glacial melt and rainfall runoff. Four lagoons present around the coast were formed by the retreat of coastal glaciers and are believed to be more than 100 m deep. Other permanent and ephemeral lagoons of varying sizes (none large) are present. The geology of the islands is not well understood, given that most of Heard Island is permanently covered in ice. A number of different geological formations have been proposed. The active vulcanism on both Heard and McDonald Islands is rare in the sub-Antarctic.

The McDonald Islands lie approximately 40 nm to the west at 53°03′ S, 72°36′ E. Formerly three islands, volcanic activity since the 1990s has resulted in lava flows connecting Flat Island with McDonald Island, a significantly altered coastline to the joined islands, and an elevation increase to McDonald Island by as much as 100 m. The extent of McDonald Island has doubled to 2 km^2 because of this activity. The volcanic activity is believed to have destroyed all vegetation on the island, based on ship-based observations in 2002. There have been just two recorded landings on McDonald Island, the first in 1971 and the second in 1980. There were and are presently no bodies of water, permanent ice, or rivers on the McDonald Islands.

The climate for both islands is maritime, with high annual rainfall and strong winds (gusts over 65 km/hr^{-1} have been recorded with automatic weather stations on the mountain slopes). Mean annual rainfall at Atlas Cove, the station occupied for the 1947–1954 period, was 1380 mm, with some form of precipitation occurring on 75% of days. The mean air temperature at Atlas Cove for the period 1948–1954 was 1.2°C, but had increased to 2.1°C for the 1997–2000 period. Limited data prevent the determination of corresponding change in the sea-surface temperatures for the area.

The fauna and flora for the islands are generally less well developed than other sub-Antarctic islands due to the isolation, climate severity, and limited ice-free habitat. A total of twelve species of vascular plant have been recorded from the islands, and the plant community is expected to increase in extent and diversity as the glacier retreat continues and further ice-free areas are formed. The invertebrate fauna are relatively poorly known and the marine species surrounding the islands have been investigated. The seabird and seal community has received perhaps the greatest research effort during the human presence on the island. There is a rapidly increasing population of Antarctic fur seals *Arctocephalus gazella* present, and the population of southern elephant seals *Mirounga leonina* has decreased by more than half since 1947. The factor(s) behind these changes are presently unknown. The population of king penguins *Aptenodytes patagonicus* has increased since first recorded in 1947, as has the breeding population of black-browed albatross *Thalassarche melanophrys*. Few other long-term data are available.

Heard Island was discovered on 23 November 1853 by Capt John Heard on the barque *Oriental* en route between Boston and Melbourne, following the adoption of great-circle shipping routes to Australia. On 4 January 1854, Capt. William McDonald on the *Samarang* discovered the McDonald Islands. Sealing activities began on Heard Island in 1854/1855, with southern elephant seals killed for their blubber. More than 40 vessels, 62 from the US, brought oil on 79 voyages from Heard Island in the period 1854/1855–1880/1881, and almost 93,000 barrels of oil were shipped from the island.

A research station was established at Atlas Cove in the northwest of Heard Island in December 1947, and was occupied until 1955 when the station was abandoned in favour of the opening of Mawson station in the Antarctic. Sovereignty of the island was transferred from the United Kingdom to Australia coincident with the opening of the station; however, the US does not recognise this claim and there are no other claimants. The wintering parties of fourteen men undertook extensive biological, meteorological, glaciological, and atmospheric research. Several brief summer and private expeditions visited Heard Island until the mid-1980s, when research efforts on the island reemerged. Recent expeditions have examined the impact of climate change on the island's glaciers and biota, further investigated ecosystem dynamics as it relates to existing fisheries, and documented the sealers' relicts scattered around the island. Fare-paying tourists have visited the island on several occasions in the 1990s, but the unpredictable weather, relative isolation, and difficult conditions ashore have minimised the visitation to date.

The islands are listed on the Australian Federal Register of the National Estate (as of 1983) and were inscribed on the United Nations World Heritage Register in 1997. In October 2002, the islands and 65,000 km^2 of the surrounding marine area were declared a Commonwealth Reserve under Australian legislation; this is the second-largest marine reserve in the world. Consideration is presently being given to nominating the territory as a wetland of international importance under the Ramsar Convention.

Eric J. Woehler

See also **ANARE/Australian Antarctic Division; Antarctic Fur Seal; Black-Browed Albatross; King Penguin; Polar Front; Sealing, History of; Southern Elephant Seal; Volcanic Events; Volcanoes**

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HEATED GROUND

Areas of geothermal activity are unusual in the Antarctic. On the continent itself, they are limited to volcanoes in Victoria Land (Mounts Erebus, Melbourne, and Rittmann) and, possibly, unknown sites currently below ice sheets. Other sites of activity are associated with active tectonic plate boundaries in the seas of the maritime Antarctic, including the South Sandwich archipelago (all volcanic in origin, with up to ten of the major islands showing contemporary activity), Deception Island (South Shetland Islands), and Bouvetøya. Much more remote from the Antarctic continent, sub-Antarctic Marion and Heard Islands also display eruptive volcanic activity. Across these sites, a range of terrestrial and freshwater habitats are found, including areas of diffuse heated ground, fumaroles, heated pools, and geysers, which have been the focus of a very limited number of ecological studies. The existence of active submarine vents is also confirmed; although not studied, exceptional biological communities analogous to those of "black smokers" on midoceanic ridges elsewhere would be expected.

Sites of geothermal activity provide unique habitats in the Antarctic, the year-round heating and liquid water overcoming two of the major environmental constraints to life elsewhere in the region. Exceptional biological communities develop near to them. In maritime Antarctic localities these consist of lush growth of diverse mosses and liverworts, dominated by sub-Antarctic or Fuegian taxa such as *Campylopus* spp., *Ditrichum* spp., and *Cryptochila grandiflora,* otherwise unknown away from these habitats in the Antarctic. Species that are common on nonheated ground elsewhere in the Antarctic are also well represented, and basidiomycete fungi (toadstools) also show exceptional levels of abundance. Likewise, the terrestrial invertebrate fauna includes mites and springtails known elsewhere only from milder sub-Antarctic locations. The lack of higher plants (other than on Deception Island and Candlemas Island, South Sandwich Islands) distinguishes these communities from temperate, tropical, and Arctic analogues. Zonation in relation to temperature, indicative of different ecophysiological limitations across species, can be particularly well developed. Heated ground communities on the slopes of Victoria Land volcanoes are more limited, including algae and other microbial groups, and the earliest stages of development of mosses (again including *Campylopus* sp.).

Specific sites of activity, and their plant and animal communities, are transient on a timescale of years to decades. Even at active sites, the speed and magnitude of temporal variation in heating can be large, highlighting the need for physiological flexibility required of biota. Short- and long-range colonisation of new locations maintains species presence. As with newly emergent habitats elsewhere in the world (e.g., Surtsey, Krakatoa), initial colonisation is rapid. Habitats are also extremely limited in three dimensions, as temperature gradients with increasing depth are often spectacular and can reach 50°C–75°C at depths as little as 2.5 cm below the vegetation surface. Only the upper 1–2 cm of bryophytes growing in some locations will be alive, even though deeper accumulations representing growth over several years can be found. Hotter soils, approaching 100°C, and the vicinity of fumarole vents emitting superheated steam, are colonised by microbial communities.

It is clear that the presence of heat and water in these exceptional habitats allows the persistence of species that are unable to survive elsewhere in the Antarctic. While individual sites of activity and their communities are transient, areas such as the South Sandwich Islands, where island age ranges up to 3 million years, may have allowed the persistence of Antarctic species through periods of greater environmental extremes, such as those during recent Pleistocene glacial maxima. Over longer timescales, volcanism has been widespread throughout the Tertiary period in the South Shetland Islands and parts of the northern Antarctic Peninsula, giving further potential for long-term biological survival in the region.

PETER CONVEY

See also **Bouvetøya; Deception Island; Heard Island and McDonald Islands; Liverworts; McMurdo Volcanic Group; Mosses; Parasitic Insects: Mites and Ticks; South Sandwich Islands; Springtails; Volcanoes**

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HILLARY, EDMUND

The son of a journalist–beekeeper and a schoolteacher, Edmund Percival Hillary was born on July 20, 1919, in Auckland, New Zealand, and grew up in Tuakau, a small country town nearby. As a boy he was an avid reader of books about adventure, and his passion for climbing began at the age of sixteen, when he first saw snow, on a school trip to Mount Ruapehu (9174 feet; 2797 m). After 2 years at university he joined his father and brother Rex in the family beekeeping business, and during World War II he served in the Pacific as a navigator for the Royal New Zealand Air Force. During the 1940s he completed many successful climbs in New Zealand's Southern Alps and in 1951 travelled to the Himalayas with a New Zealand expedition. He then joined the British Everest Reconnaissance Expedition, which was led by legendary climber Eric Shipton, one of Hillary's childhood heroes. On 30 September 1951, Hillary and Shipton were the first to see a possible southern route to the summit of Mount Everest from the Khumbu Glacier.

In 1953 Edmund Hillary and fellow New Zealander George Lowe were invited to join the British Everest Expedition, led by Sir John Hunt. Eric Shipton had described Hillary as having "summit potential" and on May 29, 1953, Hillary and Tenzing Norgay reached the top of Mount Everest (29,028 feet; 8850 m). Hillary's photograph of Tenzing standing on the summit, flags fluttering from his ice-axe, became one of the defining images of the twentieth century.

The success of the climb changed Hillary's life forever—he became both an international celebrity and a local hero. He was knighted by Queen Elizabeth II, received awards and honours from many countries, and in September 1953 married Louise Rose, daughter of Jim Rose, the president of the New Zealand Alpine Club. It was to be a very happy marriage.

In May 1955 the government of New Zealand formed the Ross Sea Committee to manage New Zealand's involvement in Antarctica during the International Geophysical Year and to provide support for the Commonwealth Trans-Antarctic Expedition. Hillary was invited to lead the New Zealand part of the expedition. He met Dr. Vivian Fuchs in Britain and traveled to Antarctica with him on *Theron* in December 1955, when Shackleton Base was established.

The New Zealand party was to establish a base on the Ross Sea in Antarctica, and travel across the Ross Ice Shelf and up onto the Polar Plateau, establishing depots of fuel and food for the British crossing party. They would meet at Mount Markham, 250 miles south of Scott Base, in November 1957. Hillary viewed the depot-laying as a fairly modest requirement, and in July 1955 he wrote from London to the Ross Sea Committee: "although the journey objective of the New Zealand end must be the establishment of a dump at Mount Markham . . . the expedition should have sufficient supplies and equipment so that if organisation and time permits, or an emergency occurs, the Party could travel out as far as the South Pole" (Hillary 1999).

On New Zealand's Tasman Glacier, Hillary's team trained in skiing, dog-sledging, flying ski-planes, and working with Ferguson tractors. They arrived in Antarctica in January 1957 well-prepared and Scott Base was speedily established using prefabricated, insulated buildings. Over the winter, Hillary's engineers and mechanics adapted the five 28-horsepower Ferguson tractors for polar travel by adding full tracks, roofless canvas cabs, and tow bars. They also built a towable shelter that they called the "caboose."

The tractor party left Scott base on October 14, 1957, with three tractors and a Weasel, each towing almost eleven tons. They crossed the ice shelf and traveled up the 100-mile Skelton Glacier to arrive at their Plateau Depot on 31 October. On the Polar Plateau they established three more depots: Midway Depot, Depot 480, and Depot 700, the last of which was 500 miles from the South Pole. They had continual mechanical problems, were plagued by sastrugi and soft snow, and were regularly required to extricate tractors from crevasses. Hillary credited his engineers, Murray Ellis and Jim Bates, for keeping their small vehicles rolling in extremely difficult conditions.

Having completed the tasks required of him by 16 December, and with Fuchs' party still at South Ice, 500 miles on the other side of the South Pole, Hillary decided to press on south. At 12:30 PM on January 4, 1958, after 10 weeks of driving "like three tiny black ants across the snowfields of eternity," the New Zealand team of Hillary, Ellis, Bates, Peter Mulgrew, and Derek Wright rolled into the Pole Station. They were the first to reach the South Pole overland since Captain Robert Scott in 1912.

The British media criticized Hillary's drive to the Pole, which was construed as a race with Fuchs. But in 1961 the British *Alpine Journal* review of Hillary's book about the expedition, *No Latitude for Error,* concluded: "In this book we learn for the first time how the original concept was transcended, by Hillary's vision and thrustfulness, from a mere depot-laying chore into an ambitious and mettlesome exploit of which the New Zealanders can be justly proud" (Banks 1961). Hillary met Fuchs and the British team at the South Pole on January 20, 1958, and guided them back to Scott Base from Depot 700. Of the fifty drums of fuel the New Zealand party placed at the depots, only twenty were needed by the crossing party.

On a joint scientific and mountaineering expedition in 1961, Sir Edmund received a request from a Sherpa friend that he build a school for Sherpa children. It was the beginning of a new focus for his life. In the ensuing 40 years Hillary's Himalayan Trust has completed scores of aid projects with the Sherpa people. It has built schools, hospitals, clinics, bridges, and airstrips; repaired and rebuilt monasteries; recruited voluntary doctors; trained and equipped teachers and nurses; and provided tertiary scholarships for Sherpa youth. Louise Hillary was closely involved in all the Himalayan Trust projects and often visited Nepal, but in 1975 Louise and their daughter Belinda, then aged 16, were killed in an airplane crash at Kathmandu. Sir Edmund and his two surviving children, Sarah and Peter, took several years to recover from this personal disaster, and Hillary immersed himself in completing projects with the Sherpas who shared his loss and grief.

In 1985 Hillary was made New Zealand's High Commissioner to India, a post he held for 4 years. In 1989 he married June Mulgrew, widow of one of his Antarctic companions, Peter Mulgrew. Despite his focus on work in Nepal, Hillary has remained closely involved with Antarctica. His son Peter is a climber who has twice climbed Mount Everest and, like his father, has travelled overland to the South Pole. In 1967 Hillary led a New Zealand climbing team that made the first ascent of Mount Herschel (11,700 feet; 3566 m) in the Admiralty Range, and in November 2004 at the age of 84 he visited Antarctica to open the new Hillary Field Centre, commemorating his establishment of Scott Base in 1956.

Alexa Johnston

See also **British Antarctic *(Terra Nova)* Expedition (1910–1913); Commonwealth Trans-Antarctic Expedition (1955–1958); Dogs and Sledging; Fuchs, Vivian; Ponies and Mules; Ross Ice Shelf; Ross Island; Scott, Robert Falcon**

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HISTORY OF ANTARCTIC SCIENCE

Antarctic science draws on most branches of knowledge, but is also an entity in itself. This is mostly because scientists, both physical and biological, working in this remote part of the world, usually have to share common facilities. Social bonding is evident in the many Antarctic clubs, societies, and institutions, some of which have existed for many years, holding meetings and issuing publications that often cover many different topics all together.

However, a single starting point can be found in one person. In 1699 Edmund Halley, in his magnetic survey of the South Atlantic, sailed to within 200 miles of South Georgia. He saw icebergs and recorded meteorological, marine, and biological features, but did not make any great contribution to Antarctic science directly. It was his wide outlook and lasting influence that were important. His demonstration that voyages made purely for scientific purposes were well worth government support led to Captain James Cook's being sent by the British Admiralty in HMS *Endeavour* to observe from a favourable spot the transit of Venus that he, Halley, had predicted would occur in 1769. This did not add any knowledge about Antarctica, but the government's interest in obtaining information about the southern seas led to the *Endeavour* voyage's being followed up by a circumnavigation by Cook in the ships *Resolution* and

Adventure (1772–1775). This yielded precise charting of the regions up to the Antarctic ice-edge, together with observations on weather, currents, ice movements, islands and their plants, and animals. Halley's influence extended even further than this. He had made the whole world his observatory, and is justly regarded as the founder of geophysics, a science that has subsequently provided the major impetus for large-scale Antarctic investigations even up to the twenty-first century.

Following Cook there was Fabian von Bellingshausen, dispatched by Tsar Alexander I with the two ships *Vostok* and *Mirnyy* to circumnavigate the southern oceans. Bellingshausen achieved a voyage (1819–1821) that was, in H. R. Mill's words, "a masterly continuation of that of Cook, supplementing it in every particular, competing with it in none." However, his imperial master had given him little time for preparation but an enormous list of scientific tasks, and he had to sail short of naturalists. Nevertheless, Bellingshausen was first to record volcanic activity in the Antarctic, probably first to see the continental ice shelf, and an assiduous observer of meteorological and marine conditions, magnetic data, birds, seals, and whales.

Around this time many ships from the United States and Britain were searching the Peninsula region for seals, but tended to keep their movements secret and recorded little of scientific interest. James Weddell was an exception, with an enquiring and accurate mind. In 1823 he reached a latitude in what is now known as the Weddell Sea of 74°15′ S, which was to remain the farthest south in that area for nearly 90 years. He wrote a book, charting many coasts and recording magnetic data, ice situations, and distribution of fauna. The first overt American exploring expedition to the Antarctic was commanded by Benjamin Pendleton and Nathaniel Palmer and sailed in the sealing brigs *Seraph* and *Annawan* in 1829. It achieved little in its geographical objectives and only one of its "scientific corps," James Eights, made any worthwhile contribution. He collected rocks, lichens, and many marine animals and wrote five papers in professional scientific style. He discussed the transport of rocks and animals by drifting ice (anticipating Charles Darwin by 6 years), expressed clearly the modern view on the origin of ice shelves, described the geology of the South Shetlands, discovered the first Antarctic fossil, pioneered studies of Antarctic invertebrates, and provided the first scientific record of a flowering plant in Antarctica. It is extraordinary that his work was almost unknown for nearly 100 years.

Another voyage with a specific scientific object was that of HM *Chanticleer* under the command of Captain Henry Foster, FRS, to make geodetic measurements. The voyage in the South Atlantic included a stay of nearly 2 months on Deception Island in 1829. The surgeon, Dr. William Webster, was deputed to be naturalist. Besides pendulum data there were accounts of geology and geothermal events and observations on plants and animals. Around this time the British sealing firm of Enderby was sending out ships, beyond financial prudence but captained by men of education and naval experience. John Biscoe in the years 1830–1832 circumnavigated Antarctica, mostly south of Bellingshausen's track, confirming that large landmasses existed. Other Enderby men made considerable geographic discoveries but added little science, except that John Balleny's report provided Darwin with information on the transport of rock by an iceberg (1839).

In the mid-nineteenth century, science generally was developing apace and Antarctic science had a burst of activity for 6 years. Three nations were involved. In the United States, New England merchants were keen to find new sealing and whaling grounds and eventually persuaded Congress, with drawn-out argument, to support an expedition to the Pacific Ocean and the south seas. Lieutenant Charles Wilkes, with much disapproval since although he had a tendency to science he was a junior officer, was eventually put in command. His unsafe flotilla of ships was led by USS *Vincennes,* which spent a total of about 3 months in Antarctic waters during its cruise of 1838–1842.

In France the explorer and scientist Captain Dumont d'Urville was keen to go on another voyage to study Pacific ethnology and was taken aback when King Louis Phillippe readily agreed to give support, with the condition that there should first be an attempt to reach the South Pole, evidently for the glory of France. The expedition was launched in two corvettes, *Astrolabe* and *Zélée,* with dispatch and no argument (1837–1840).

After the Napoleonic wars, the Royal Navy had been left with a surplus of men and ships. Some of these had been deployed to explore the Arctic, mainly under the powerful influence of John Barrow, the Second Secretary of the Admiralty and an enthusiast for exploration, who was also able to promote an expedition south. Behind the political machinations that launched all three of these ventures were scientific plans. The power lay firstly in the Baron Alexander von Humboldt (1769–1859). He was widely travelled—he wanted to visit Antarctica himself but did not succeed—and has been described as the last complete scientist: an expert on geomagnetism, geology, and botany, a pioneer in climatology, oceanography, and biochemistry, and of techniques such as isothermal plotting, geological mapping, and numerical analysis of data. He was particularly enthusiastic about terrestrial magnetism and had himself observed the connection between auroral display and variation in horizontal magnetic intensity. He was in close contact with C. F. Gauss and W. Weber at Göttingen, the leading organizers in the field. Such was his influence that his proposal for a chain of geomagnetic observatories stretching across Russia was taken up by the authorities in St. Petersburg. The United States and Europe from Ireland to Germany already had networks of similar stations, and Humbolt realized that to complete the encircling of the Earth he had to persuade the British government to establish stations in its overseas territories. He had no difficulty with this. The Royal Society and the British Association for the Advancement of Science gave support to "the Magnetic Crusade," and the government, under Barrow's influence, was willing to equip an expedition under James Clark Ross, who had recently located the North Magnetic Pole, to make observations in the Antarctic, setting up stations in British Territories on the way (1839–1843). The two ships, HMS *Erebus* and *Terror,* were fitted to penetrate the ice and were well equipped.

The Americans and French also had magnetic observations as major objectives; both countries had contacts with Humboldt, but did not have the British Fox dip circle, which could measure declination, dip, and intensity with acceptable accuracy on a vessel at sea. The US ships provided evidence of land of continental extent within the Antarctic Circle. Their contributions to Antarctic geology and biology were slight—Wilkes left his biologists behind when he went south, deeming that there would not be much for them to do. The expedition's greatest scientist, James Dwight Dana, made observations in the Pacific that later were to contribute to the theory of plate tectonics, and it was he who described the type specimen of *Euphausia superba,* now familiar as the Antarctic krill. The French made valuable observations on meteorology and ice formations, and their reports on zoology and biology were beautifully illustrated, with crabeater seals *(Lobodon carcinophagus)* being a notable discovery.

The provision of definitive charts of magnetic determinations was a major achievement of Ross's expedition on *Erebus* and *Terror*—measurements were checked daily between the two ships. Their work enabled the Gaussian theory of the Earth's magnetic field to be revised to fit the Southern Hemisphere. Before the ships had sailed, the Royal Society had set up committees for physics, meteorology, geology and mineralogy, botany and vegetable physiology, and zoology and animal biology. Their recommendations were incorporated into an eighty-five-page booklet with some sections so useful as to be reissued for general use. Humboldt had written to the Admiralty giving many valuable suggestions, especially regarding the critical facts that seawater does not have the same point of maximum density as freshwater and that pressure on thermometers at depth distorts the readings. Unfortunately, his letter arrived after the expedition had sailed. There were no professional scientists aboard ship, it being assumed that officers would take care of the physical side and the surgeons the geology and biology. Ross himself was an expert in magnetism and had a bent towards natural history. Among the natural historians was Joseph Hooker, twenty-two when he sailed, an ardent botanist who had taken a year's course in medicine simply to enable him to voyage in foreign parts. He collected plants whenever possible, and back in England he quickly produced *Flora Antarctica* (1847)—still referred to today—but at sea he collected marine life and made drawings for Ross. He drew attention to the fact that diatoms are plants, not animals as was supposed, and that they are the primary producers of the oceans. To the present biological oceanographer, this is the greatest discovery of the nineteenth century. Information, useful when corrected as suggested by Humboldt, on physical oceanography was obtained by the officers. The discovery of the Ross Ice Shelf (or Great Ice Barrier as it was originally known), which is floating at its seaward edge, was momentous. Rocks were collected assiduously, many from crops of penguins. A book on the larger animals was published, but the material collected for Ross, planktonic and benthic, was, sadly, lost.

The scientific achievements of these three expeditions were considerable. Magnetic studies were carried out to similar programmes, and there was some exchange of information, although patriotic rivalry ran high. None undertook any land exploration.

Following this, there was an "age of averted interest" for almost 50 years. No real prospects of colonisation or commercial promise attracted any nation farther south, and scientists themselves seemed to have no wish to probe any further. After their return, both Ross and Hooker made it evident that they found no problems calling for further attention, and, rather surprisingly, said that they did not expect anyone to visit again the regions that they had penetrated. It was certainly not that science was becoming quiescent. Humboldt's efforts to advance physical geography had, however, become unfashionable, and interest in terrestrial magnetism had dwindled. A lone voice raised on behalf of the Antarctic was that of the American maritime meteorologist Matthew Maury (1869). He realised that the high southern latitudes provided the key to the weather of the Southern Hemisphere, but nothing came immediately of his efforts to organise research.

The incursion of the *Challenger* Expedition (1874) into the Antarctic yielded much from its dredging of bottom deposits about the geology of the continent and the nature of the Southern Ocean. Interest began to strengthen late in the nineteenth century. Karl Weyprecht, coleader of the Austro-Hungarian Exploring Expedition (1872–1874), gave deep thought to the general problems of polar research while beset off Franz Josef Land, concluding that detailed topography was of secondary importance, that the geographic pole did not have greater value for science than any other point at high latitude, and that decisive scientific results could only be obtained by a series of synchronous expeditions distributed all over the polar regions. He put this view before various academies without effect until it was taken up at an International Meteorological Congress in 1879, leading eventually, after he died in 1881, to the first International Polar Year (1882). Included in this was a German expedition to South Georgia for a full year. This did excellent work on meteorology, magnetics, glaciology, marine and terrestrial flora, and ornithology. Dr. Georg von Neumayer, Director of the Deutsche Seewarte at Hamburg and an enthusiastic campaigner, had given support to this, and at the Sixth International Geographical Congress, held in London in 1895, spoke at length on Antarctic science, expressing the hope for international collaboration in organising expeditions. In a later lecture to the Royal Society, he made a remarkably foresighted comment that studies of geomagnetism and atmospheric electricity would be particularly important in the Antarctic. British scientists, including Sir John Murray (of *Challenger*) and Sir Clements Markham (President of the Royal Geographical Society) strongly supported Neumayer's suggestions. Things then began to happen. Whalers made exploratory cruises south from 1892 onwards, but their attitude to science was sometimes unhelpful. The voyages of *Belgica* (1897–1899), *Valdivia* (1898–1899), and *Southern Cross* (1898–1900) all contributed useful science, but the continent itself was only marginally touched.

The Heroic Age followed. The major scientific expeditions were the German Antarctic Expedition (*Gauss,* under Erich von Drygalski, 1901–1903), the Swedish South Polar Expedition (*Antarctic,* under Otto Nordenskjöld, 1901–1904), the British National Antarctic Expedition (*Discovery,* under Robert Falcon Scott, 1901–1904), the Scottish National Antarctic Expedition (*Scotia,* under William Speirs Bruce, 1902–1904), the French Antarctic expedition (*Française,* under Jean-Baptiste Charcot, 1903–1905), the British Antarctic Expedition (*Nimrod,* under Ernest Shackleton, 1907–1909), the second French Antarctic expedition (*Pourquoi-Pas?,* under Charcot, 1908–1910), the British Antarctic expedition (*Terra Nova,* under Scott, 1910–1913), the second German South Polar Expedition (*Deutschland,* under Wilhelm Filchner, 1911–1912), the Australasian Antarctic Expedition (*Aurora,* under Douglas Mawson, 1911–1914), and the Imperial Trans-Antarctic Expedition (*Endurance,* under Shackleton, 1914–1916). All had undertaken scientific work to attract support, and most produced substantial reports, some running to ten or more weighty volumes. Even the unfortunate *Endurance* managed several worthwhile papers, although Roald Amundsen's brilliant attainment of the South Pole in 1911 produced no science of significance.

Although there had been some preliminary consultation between nations, the only major overlap of individuals on these expeditions was between Scott and Shackleton, and Shackleton and Mawson, but in the event these were of no importance scientifically. Four of the expeditions did not have established land bases for research, and only five had "well-found" laboratories ashore. Several concentrated on oceanography. In general, however, there was good spread among the sciences, from physics and chemistry to geology and biology. Comparison of the quality of the science is rather pointless; the expedition on *Scotia,* led by a scientist, produced the largest number of high-quality publications, but the bulk was specialised zoological work, whereas that on *Discovery,* although it also did much zoological work, produced beyond this reports covering a wide range, establishing basic knowledge of the continent itself. There had been questions as to whether a scientist or naval officer should be in charge of such expeditions. The bitter quarrel between Markham and the Royal Society on the subject is not a strictly scientific topic, but it is a reasonable surmise that a good naval captain, Scott, with no scientific training but an innate feeling for science was better than an eminent geologist who might have put his own subject first. At least Scott did his best to ensure on his fateful return from the Pole that the fossils collected by Edward Wilson, eventually found to include *Glossopteris*—evidence of continental drift—should reach the British Museum.

Following the Heroic Age, there was an effective step toward the organisation of polar science in the foundation of the Scott Polar Research Institute in Cambridge in 1920. Two of Scott's men, Raymond Priestley and Frank Debenham, together with Shackleton's geologist, James Wordie, set up a centre for collecting polar information. Now, in the twenty-first century, it does research on its own account and has the best polar library in the world. Heroic Age tradition still lingered on in two modest expeditions. T. W. Bagshaw and M. C. Lester wintered (1920–1922) on the Antarctic Peninsula in a hut knocked together from an old boat and some packing cases, and yet collected a prodigious amount of useful data. The British Graham Land Expedition (1934–1937) carried out some excellent science, although the biologists had to make do with a balance made from a wooden beam poised on a pebble ground to a knife edge.

There were two major advances in the period between the two World Wars. At the beginning of the century, Scandinavians had pioneered oceanography in the Arctic seas, and the expeditions just mentioned had followed this with much data about the Southern Ocean. W. Meinardus, using more than half a million measurements obtained by *Gauss,* identified the Meinardus Line, later called the Antarctic Convergence. The *Discovery* Investigations extended Antarctic oceanography, both on the physical and biological sides, working intensively in the 15 years after 1926. It came into being because whaling was developing rapidly on the South Atlantic, and the British government realised that management was necessary if the industry was not to collapse as it had done in the north. For once the civil service understood the needs of science and proposed far-reaching research with ample financial support. The results were excellent: among the outstanding scientists were George Deacon, who worked out the pattern of circulation in the Southern Ocean, and Alister Hardy, who invented the plankton recorder that was used to effect in the south and is now employed over most of the world's oceans. The other major advance was American, on three expeditions in 1928–1930, 1933–1935, and 1939–1941, led by Richard E. Byrd and financed on a substantial scale. They were not the first to use radio, mechanised surface transport, and aircraft in the Antarctic, but they were first in using these effectively and extensively. Work was carried out over wide fields, beginning a more efficient era in Antarctic science. Contributions in geology, meteorology, ionospherics, and microbiology were particularly outstanding.

The urgent demands of the Second World War produced more equipment and techniques adaptable to polar conditions. After the war, these were used on massive scale by the US, involving icebreakers, advances in meteorology, and flying techniques extending to helicopters and aerial photography. However, at this time the US interest was, frankly, military. *Operation Highjump* (1946–1947) used 4700 men, 13 ships, and 9 aircraft in the Antarctic, but produced just three scientific papers. Science began again with the Norwegian–British–Swedish Expedition of 1949–1952, a private venture that was the beginning of good international cooperation, putting well-planned science before geographical exploration. It was the first to obtain reliable systematic seismic sounding of ice thickness in Antarctica. Apart from that, some national stations were being established. The British Operation Tabarin, set up by Winston Churchill to keep an eye on the Antarctic Peninsula and surroundings, had been changed into the Falkland Islands Dependencies Survey and began scientific work. Later it was renamed, for political correctness, the British Antarctic Survey, and has become one of the outstanding organisations for Antarctic research.

The mid-twentieth century saw a momentous development, with the International Geophysical Year (IGY) set up to study ionospherics and geomagnetism with special attention to the Antarctic. Governments gave support, and there were brought together in July 1957 scientists of 64 nationalities, involving 4000 stations, 55 of these, from 12 countries, being in Antarctica. Vast amounts of data were accumulated and in the course of time led to spectacular advances in geophysics. Other important results were that it helped lead to the Antarctic Treaty, which effectively neutralised quarrels over terrestrial claims and established a continent reserved for science.

Nations were anxious to keep foot in Antarctica and carried on research there after the cessation of the IGY. The Scientific Committee on Antarctic Research was set up to advise the treaty organisation. Other subjects were quickly added to ionospherics and geomagnetism, geology being foremost but oceanography, terrestrial, and atmospheric physics and chemistry, glaciology, meteorology, biology, and medical studies being included. Subjects were, of course, brought up to date, and some led the field. An example might be ornithology. Hitherto this had been mainly for naturalists, but Antarctic birds are particularly amenable to study, being large, unafraid of man, tolerant of handling, and breeding in large numbers in accessible colonies. Sophisticated physiological and ecological techniques, such as attachment of instrument packages and satellite telemetry, enable populations and behaviour to be quantified. This work has been of worldwide value in establishing the role of seabirds in the marine ecosystem. Marine biology is, in fact, an Antarctic science with a commercial impact. Overfishing in southern waters calls for conservation. The Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR), based on sound ecology and set up by the treaty, includes stringent control measures that came into operation in 1980. Another example, largely an international operation, is ice drilling, yielding cores down to more than 3000 m. Ice samples contain air, dust, and other materials from which chemical analyses give measurements of climate at precisely determined dates extending more than 740,000 years. The cyclic processes revealed are of great value in indicating what future climatic changes may be.

A feature of Antarctic research during the last 30 years is that, as elsewhere in the modern world, it is mainly done by teams carrying out carefully planned programmes with elaborate equipment and steered by a committee via radio and satellite. Nevertheless, some of the most exciting discoveries in the last half-century have been made by chance or individuals. After 50 years of indifference since Scott found them, the Dry Valleys were opened up first to geology and then to limnology, microbiology, and exobiology by two obstinate young New Zealanders, B. C. McKelvey and P. N. Webb (1957). It cost a geologist who had not been south difficulty in persuading the US National Science Foundation that the extraordinary collection of meteorites on Antarctic ice was possibly of interest. The "ozone hole" over Antarctica in the austral spring was discovered by British Antarctic Survey atmospheric chemists persisting with a rather dated technique when satellite monitoring produced so much data that the events recorded over the Antarctic escaped notice. Such items of history are worth bearing in mind by scientists.

G. E. Fogg

See also **Antarctic Treaty System; Australasian Antarctic Expedition (1911–1914); Belgian Antarctic *(Belgica)* Expedition (1897–1899); Bellingshausen, Fabian von; Biscoe, John; British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); British Antarctic *(Nimrod)* Expedition (1907–1909); British Antarctic *(Southern Cross)* Expedition (1898–1900); British Antarctic Survey; British Antarctic *(Terra Nova)* Expedition (1910–1913); British Graham Land Expedition (1934–1937); British Imperial Expedition (1920–1922); British National Antarctic *(Discovery)* Expedition (1901–1904); *Challenger* Expedition (1872–1876); *Chanticleer* Expedition (1828–1831); Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Cook, James; Crabeater Seal; Debenham, Frank; Deception Island; *Discovery* Investigations (1925–1951); Dry Valleys; Enderby, Messrs.; French Antarctic *(Français)* Expedition (1903–1905); French Antarctic *(Pourquoi Pas?)* Expedition (1908–1910); French Naval (*Astrolabe* and *Zélée*) Expedition (1837–1840); German South Polar *(Deutschland)* Expedition (1911–1912); German South Polar *(Gauss)* Expedition (1901–1903); Hooker, Joseph Dalton; Imperial Trans-Antarctic Expedition (1914–1917); International Geophysical Year; International Polar Years; Markham, Clements; Neumayer, Georg von; Norwegian–British–Swedish Antarctic Expedition (1949–1952); Palmer, Nathaniel; Priestley, Raymond; Royal Geographical Society and Antarctic Exploration; Royal Society and Antarctic Exploration and Science; Russian Naval (*Vostok* and *Mirnyy*) Expedition (1819–1821); Scientific Committee on Antarctic Research (SCAR); Scott Polar Research Institute; Scott, Robert Falcon; Scottish National Antarctic Expedition (1902–1904); Swedish South Polar Expedition (1901–1904); United States Antarctic Service Expedition (1939–1941); United States (Byrd) Antarctic Expedition (1928–1930); United States (Byrd) Antarctic Expedition (1933–1935); United States Exploring Expedition (1838–1842); United States Navy Developments Projects (1946–1948); Weddell, James; Wilson, Edward; Wordie, James**

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HOOKER, JOSEPH DALTON

Joseph Dalton Hooker was born at Halesworth, Suffolk, on June 30, 1817, the second son of William Jackson Hooker and his wife Maria Sarah. Educated at Glasgow High School and then Glasgow University, where his father was professor of botany, Hooker graduated with an MD in 1839 and managed to combine his enthusiasm for botany with travel by joining James Clark Ross's expedition to Antarctica as the botanist and assistant surgeon. During 4 years exploring the Southern Ocean, Hooker made crucial plant collections from many remote places. When *Erebus* returned in 1843, he began work on the *Botany of the Antarctic Voyage,* which eventually comprised six volumes, two each for the sub-Antarctic islands, New Zealand, and Tasmania. His father, by then director of the Royal Botanic Gardens at Kew, was unable to support him and the production of these key volumes was achieved on his pay as an assistant surgeon. He worked for 2 years for the Geological Survey, but then gained a government grant to collect plants in the Himalayas (1847–1849).

In 1851, Hooker married Frances Harriet Henslow, daughter of the professor of botany at Cambridge. They had six children, but Frances died in 1874, and 2 years later Hooker remarried to Hyacinth Symonds, with whom he had two further sons.

In 1855, Hooker was appointed assistant to his father at Kew, taking over from him as director after his father's death in 1865. He remained director until 1885. He continued to work after retirement, producing *Flora of British India* and *Handbook of the Flora of Ceylon,* as well as a book on his father and numerous scientific papers. Even his friends described Hooker as high strung and irritable, yet his capacity for hard work was well known. During his directorship, Kew consolidated its reputation as a key source for the natural materials and resources, of which perhaps the most famous was the transfer of rubber trees from Brazil to parts of the British Empire.

A very close friend of Charles Darwin, Hooker was a firm believer in evolution and pioneered phytogeography, the study of the distribution of plants. Hooker was highly regarded both by his peers and by politicians, receiving numerous honorary degrees and public honours, such as the CB in 1869, KCSI in 1877, GCSI in 1897, and the Order of Merit in 1907. The Royal Society gave him first the Royal Medal in 1854, then the Copley Medal in 1887, and finally the Darwin Medal in 1892. He received numerous prizes and awards from both British and foreign scientific societies. He died in his sleep on December 10, 1911, and was buried alongside his father at Kew Green.

DAVID W. H. WALTON

See also **British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); History of Antarctic Science; Ross, James Clark**

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HUMPBACK WHALE

Because they are active at the surface, easy to identity, and often found close to shore, humpback whales *(Megaptera novaeangliae)* are among the best known of the great whales. Surface activity is characteristic of humpback whales; they are commonly observed leaping from the water (breaching), slapping the surface with the flippers (flippering) or tail flukes (lobtailing), and lifting the head from the water (spyhopping). They are the most distinctive of the baleen whales, with flippers that extend to about a third of the body length, rounded knobs on the upper and lower jaws, and an irregular, prominently serrated trailing edge on the tail flukes. The dorsal fin is variable in shape, from tall and strongly hooked to a low, rounded lump. The dorsal surface is black, with varying degrees of white on the ventral side of the body and flukes. In some Southern Hemisphere humpbacks this white coloration extends up the flanks nearly to the dorsal fin. On diving, they regularly raise the flukes into the air. The undersides of the flukes are distinctively marked and individuals can be recognized from these natural "tags."

Humpback whales are mysticetes or baleen whales. They have no teeth, but rather use a series of horny plates called baleen, which grow from the upper gums to filter prey from the water column. Up to 400 fairly short (<1 m), dark-coloured baleen plates occur on each side of the jaw. The fringes on the inside of these plates form a thick mat for straining prey from the water. The relatively coarse fringe on humpback baleen is better suited to the capture of krill and small schooling fish than smaller zooplankton. Krill (principally *Euphausia superba*) is their preferred food in Antarctic waters; they are occasionally reported to take other invertebrates and fish, though some of this other food may be caught incidentally.

Krill form dense swarms that humpbacks take into the mouth by expanding the throat cavity. They have fourteen to twenty-two large pleats referred to as rorqual grooves that extend from the lower jaw to the navel. These allow the throat area to expand massively, engulfing krill-laden water for subsequent filtering. A wide and diverse variety of acrobatic behaviours including lunging, breaching, or lobtailing and the underwater release of bubbles are common among humpbacks during feeding and rarely observed among other baleen whales. These activities presumably concentrate prey or prevent diffusion of prey swarms. On the feeding grounds humpbacks are most often seen in clusters consisting of several small groups of one to four whales. Larger groupings are sometimes seen, particularly where food is abundant. While these whales may travel or feed together in a coordinated manner, these associations do not appear to represent social groupings and little if any group stability or coherence is observed over time.

Cosmopolitan in distribution, humpback whales are found in every major ocean basin ranging from the equator to polar waters. They occur in two distinct seasonal habitats. During the summer they are principally found in productive temperate, polar, and subpolar waters where they feed. In winter they migrate to tropical and subtropical breeding grounds for calving and mating. Thus few humpback whales occur in Antarctic waters during the winter months (May through September). However, humpbacks may well be present during every month of the year as some, particularly nonbreeders, may occasionally overwinter in the feeding grounds while others may not undertake a complete migration during some years.

Humpback whales are widespread in the productive waters from the Antarctic convergence to the ice edge. A small feeding group has also been identified along the coast of Chile, but the vast majority of Southern Hemisphere humpback whales feed in the Southern Ocean. They are found most commonly in areas where oceanographic conditions lead to exceptionally large, dense swarms of the krill on which they feed. Because the oceanographic conditions that lead to these swarms are reasonably predictable annual occurrences, humpback whales are likely to return to the same region each year. Such regular return to specific feeding areas has been documented in the Northern Hemisphere, and is thought to be widespread in humpback whales. Seven feeding areas have been proposed for the Southern Ocean. However, the boundaries between these are often obscure, with no clear gaps in whale distribution between them. Lacking detailed information on individual movements, therefore, the extent and scale of feeding-area fidelity in the Southern Ocean is not well known, and it is possible that individual humpback whales may forage over large regions of the Southern Ocean.

During the austral winter months, humpback whales leave the Antarctic and are found in one of seven low-latitude breeding grounds. It is in this region that calves are born and that mating is presumed to take place, though it has never been observed. The largest numbers of animals are found in shallow water sites near continental margins, reefs, banks, or islands. Most occur at about 20° S latitude, though along the west coast of Africa whales occur north of the equator, while the breeding area off Costa Rica, where geographical, though not seasonal, overlap with animals from the Northern Hemisphere has been shown, extends to nearly 10° N.

Because these seasonal habitats are separated by several thousand kilometres, migration is a prominent feature of humpback whale ecology. Movements of more than 8000 km by individual humpback whales from the Antarctic Peninsula to breeding areas off Central and South America are the longest documented for any mammal. Migrations have traditionally been thought to consist principally of north–south travel between feeding and breeding areas at similar longitudes, and each of the seven breeding areas has been linked with a feeding area to the south. A small number of tag returns between feeding and breeding grounds have shown substantial east–west movement, however, suggesting that animals from different breeding areas may mix on the feeding grounds. Thus, in the absence of additional data on individual movements and population genetics, the specific movement patterns and population structuring of humpback whales in the Southern Hemisphere remain speculative.

The mating system has been likened to a lek, with numerous males and females congregating in a common area and males attracting females through physical or vocal display rather than by controlling a territory. Physical display may include aggressive competition between males, while the long, complex, and highly structured song of humpback whales is produced only by males and is likely to be used as a vocal display. Social bonds do not appear to play an important role in the mating system, as neither kinship nor feeding ground affiliation has been found to influence associations on the breeding grounds. Mating is thought to be brief and no long-term bond is established between the pair. Males have no role in tending calves, and genetic tests have shown multiple calves born to the same mother to have different fathers.

Females give birth to a single calf every 2–4 years following a pregnancy lasting 11–12 months. Calves remain with the mother for about a year; the two stay in close proximity during the first summer in Antarctic waters. Calves are approximately 4–4.5 m at birth, weighing 2 tonnes. The young grow at about a half-meter each month on rich milk that contains about 45% fat. By weaning they average about 9 m. Adult humpback whales average 13–14 m in length and weigh upwards of 25 tonnes. Weight and blubber thickness vary seasonally and with reproductive condition. Humpbacks normally do not eat during migration or while on the breeding range and so must store enough blubber during the feeding season to maintain them during winter. Both males and females mature sexually at 5 years of age, continuing to grow for another 10 years or so. As in all baleen whales, females are somewhat larger than males. There are few data on life expectancy, but adult survival rates are high (0.96), and the oldest animal reported from whaling operations was 48 years of age.

Given their large size, adult humpback whales have little to fear from most predators, though calves are vulnerable to killer whales and possibly to larger sharks. A number of attacks on humpback whales by killer whales have been witnessed and visible scars from orca teeth on the flukes of many whales bear witness to further unseen attacks. These same scars, however, show that many humpbacks survive encounters with killer whales, leaving unresolved the extent and importance of predation in humpback whale ecology.

Thousands of Southern Hemisphere humpback whales were killed on the breeding range by the nineteenth-century nonmechanized whale fishery. It was not until early in the twentieth century, however, that the introduction of fast, mechanized catcher boats and deck-mounted harpoon guns opened the Southern Ocean to whaling on a scale not previously imaginable. Initially, whaling operations required a land base, and South Georgia, with secure harbours near a seemingly boundless number of whales, dominated the global industry. These technological advances also made humpback whales a primary target of the whalers, as these whales were relatively slow swimming, were often distributed near to shore, were easy to process, and yielded a large quantity of oil. During the first season of whaling at the Grytviken whaling station on South Georgia, 81% of the whales landed were humpbacks, while humpbacks accounted for 69% of total catches during the first 10 years at South Georgia. As whaling spread to other islands and the development of viable floating factories opened more remote regions to hunting, humpbacks continued to account for a disproportionate share of early catches. Whalers shifted to other species only as the more valuable humpback and blue whales declined.

The best estimates currently available suggest that in all about 200,000 humpbacks were killed in the Southern Hemisphere during the twentieth century. Catches of humpback whales peaked almost immediately after modern whaling commenced, with over 50,000 animals reported taken between 1909 and 1915. These officially reported catches may underestimate the actual number killed; as late as the 1950s, 20%–50% of the whales harpooned were not landed. Another major peak in catches occurred during the 1950s and 1960s. The extent of these takes was largely unknown at the time, as most were unreported catches made during widespread, indiscriminate whaling operations conducted by the Soviet Union. The actual catch records have only recently been made public. Between 1947 and 1972, the Soviet fleet landed well over 48,000 humpback whales in the Southern Hemisphere while reporting only 2820. About 13,000 were taken during a single season in 1959–1960.

Concerns over rapidly declining catches resulted in an end to commercial hunting of humpback whales in the Southern Hemisphere in 1963–1964, though the illegal catches continued for another decade. Because of the extent of global depletion and the uncertain extent of recovery, humpback whales are listed as vulnerable by the IUCN and trade is restricted under Appendix I of the Convention on International Trade in Endangered Species. The number of humpback whales living in Antarctic waters today is not known. The Scientific Committee of the International Whaling Commission recently presented an abundance estimate of 10,000 humpback whales south of 60° S. This is almost certainly a low estimate given the large number of whales that have been individually identified in the Southern Hemisphere. However, no better estimate is currently available.

In some areas of the Southern Hemisphere there is considerable evidence for population recovery following protection. Notably, surveys off Australia indicate dramatic increases in the number of whales migrating off both the west and east coasts. In other regions where humpback whales were formerly abundant, there is little or no evidence of recovery. Near South Georgia, for example, evidence indicates that humpbacks remain uncommon today. Because of limited shipping and fishing in the Southern Ocean, the major current causes of human-induced mortality, ship strikes and entanglement in fishing gear, are likely to be of minimal concern in Antarctic waters.

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See also **Convention on International Trade in Endangered Species of Wild Flora and Fauna (CITES); International Whaling Commission (IWC); Killer Whale; South Georgia; Whales: Overview; Whaling, History of; World Conservation Union (IUCN); Zooplankton and Krill**

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I

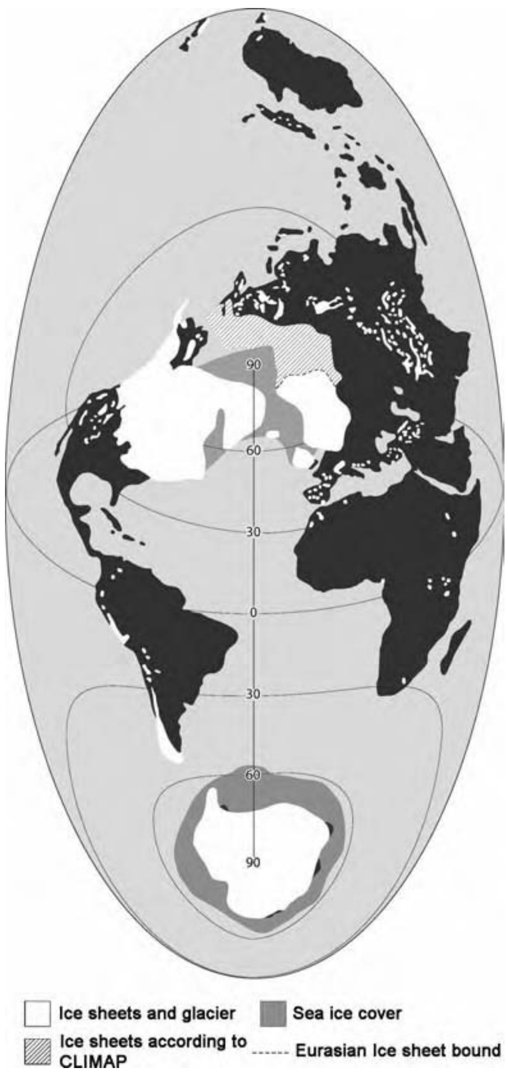
ICE AGES

The theory of ice ages, or "glacial theory," was developed in the mid-1800s by Louis Agassiz, who argued that the surface morphology of much of northern Europe and North America could be explained by processes active within glaciated environments. While his theory involved an inaccurate reconstruction of a huge single ice sheet flowing from the pole and covering much of the Northern Hemisphere, the basic principle of the theory was visionary. It was also hugely controversial. Glacial theory challenged the widely held belief that the landscape had been both created and modified by God (a theory known as diluvialism). Through scientific reasoning, however, Agassiz convinced many of the leading geologists of the time, including the Reverend Dr. William Buckland, of past glaciation. Once glacial theory had been largely accepted as a natural phenomenon, geologists began to identify the causes of ice ages.

It was twice hypothesized (by Scottish cleric James Croll in the late nineteenth century and Serbian mathematician Milutin Milankovitch in the mid-twentieth century) that changes in the Earth's orbit around the Sun would lead to reductions in the level of solar heat that, in turn, would cool the planet and result in the growth of glaciers.

While Croll was the first to propose a connection between solar inputs to the Earth and climate change, his calculations were wrong (he advocated that the last ice age occurred some 60,000 years before it actually did). His analysis was refined, however, by Milankovitch, who proposed that ice ages were forced by variation in Earth's orbit, causing changes to the amount of solar radiation received at the Earth's surface, in three ways. The first orbital variation is known as the eccentricity, or the change from an elliptical to circular orbit over a period of ~100,000 years. The second is the obliquity of the spin axis, which varies between 21.39° and 24.36° over a cycle of ~41,000 years. The third orbital change is due to the precession of the equinoxes, which affects the timing of perihelion and aphelion (the position where the Earth is closest and furthest from the Sun) with a periodicity of ~21,000 years.

On both occasions when orbital variations were proposed as the cause of ice ages, after initial recognition the idea lost favour in the scientific community. The problem is that the changes in solar input to the Earth caused by its orbital variation are so low that many found it difficult to reconcile the process with the growth and decay of huge ice sheets and the many associated changes to the physical and biological environments. Not until the 1970s was the hypothesis proven, by climate researchers looking at ocean sediments for evidence of past climate shifts. Hays, Shackleton, and Imbrie identified that shifts in the ratios of isotopes of oxygen recorded in sea-floor sediments corresponded well with the periodicities involved in Milankovitch's calculations. Although this work established the root cause of ice ages, the problem of how small changes in solar inputs lead to large changes in ice sheets and climate remained. It is thought today that solar input variations are merely a trigger for other processes acting on or near the



Ice sheets of the last glacial maximum. Note that the size of the Eurasian Ice Sheet across northern Europe and Arctic Russia is shown in both maximum (after the CLIMAP project of the 1970s) and minimum (after the QUEEN project of the 1990s) configurations. (Adapted from Broecker and Denton 1990.)

Earth's surface, which lead to positive "feedback" in the climate system. For example, small reductions in air temperature caused by solar variations lead to an increase in the snow field extent, which reduces the amount of solar energy absorbed by the Earth (as snow is quite reflective), thus further reducing air temperature. Several feedback processes have been identified, and many of them are complex and interactive. They combine to both magnify and modify the effect of Earth's orbital variations around the Sun to force huge environmental changes.

The most detailed information concerning the timing and magnitude of past ice ages comes from the deep ice cores of Greenland (for the past ice age) and Antarctica (for the past four or so ice ages). As the ratio of oxygen isotopes varies with global ice volume, by measuring this ratio in ancient ice, records of an ice age can be evaluated. Furthermore, the gas held within the former snowpack, which later densifies into ice, contains a record of atmospheric greenhouse gases, which are related to global air temperatures. Analysis of ice-core results, and their sea-floor sediment counterparts (exchange ancient calcarious organisms for ancient ice to reveal oxygen isotope ratios), has resulted in a detailed understanding of the natural climate cycles that characterise ice ages.

While ice cores have revealed how orbital variations dictate the pacing of ice ages, they have also shown that short-term climate oscillations operate around the long-term signal. For example, Greenland ice cores show temperature variations of several degrees centigrade over periods as short as a few decades. Such climate change cannot be explained by orbital forcing. Instead, the climate feedback processes that cause magnification of the orbital influence on air temperature are probably responsible. For example, as the Earth warmed during the onset of deglaciation, ice sheet decay led to enhanced fluxes of meltwater being issued to the ocean. Such was the influence of this process on the salinity of the North Atlantic that the thermohaline ocean circulation system was affected, so reducing the flow of warm water northwards and thus reversing climate warming in this region. The traditional view of climate change over a glacial cycle, involving a lengthy ($\sim$90 ka) period of cooling followed by a rapid ($\sim$10 ka) period of warming has been revised in recent years with short-term oscillations punctuating this long-term envelope.

The ultra-low rates of snow accumulation in Antarctica (being a polar desert) mean that Antarctica's subsurface ice is much older than Greenland's. Antarctic ice cores therefore provide important information about climate change extending back through several glacial cycles. The ice core at the Russian base Vostok Station goes back as far as 420,000 years (Petit et al. 1999), covering four glacial cycles, whereas a recent ice core from Dome C, drilled by the European Project for Ice Coring in Antarctica (EPICA 2004) extends this record through a further four cycles.

The time of maximum extent of the last ice sheets is known as the last glacial maximum (LGM). So much water had been taken from the ocean to form these ice masses that global sea-level was around 120 m lower than today. Clearly the cryosphere looked very different at the LGM than it does now. The greatest change was in the Northern Hemisphere, with the development of huge ice sheets over the bulk of Canada and much of the northern United States (the Laurentide ice sheet, which contributed to over 60 m in sea-level fall) and in northern Europe (the Eurasian ice sheet, which held as ice over 15 m worth of sea level). Other places also witnessed great increases in the size of ice sheets, notably in Greenland and Antarctica and across Patagonia. In Antarctica, the greatest change in the form of the current ice sheet was across West Antarctica, where both the Ross and Filchner-Ronne ice shelves became part of the grounded ice sheet that flowed in some places out to the continental margin. Numerical modelling predicts that this expansion caused sea-level reduction of 16–30 m. The bulk of this expansion occurred in West Antarctica. In East Antarctica ice growth was curtailed by the drier conditions of the last glacial cycle, which led to slight thinning in the ice sheet interior. This surface lowering was countered somewhat by growth at the ice sheet margin. The net effect of these processes was only modest enlargement of the East Antarctic Ice Sheet. Today, the processes may be reversing, as ice sheet margin retreat is more than balanced in East Antarctica by snow-driven ice-thickness increases (Davis et al. 2005).

In addition to ice sheet growth and expansion, other components of the cryosphere (sea ice and permafrost) also experienced a prolonged period of growth prior to the LGM.

Cryospheric change of this kind had a huge impact on the planet's environment. The hypsometry of several continents were changed so greatly that atmospheric airflow was affected. The ocean state was modified by both air-temperature cooling and the growth of sea-ice fields, both affecting oceanic flow. Air temperatures were, on average, around 8°C–10°C cooler. Precipitation values fell in association with this cooling. Because quite warm conditions prevailed at the equator, enhanced meridional air-temperature and atmospheric pressure gradients were set up. LGM Earth was therefore far cooler, drier, and windier than today.

Such was the level of dryness and windiness that huge levels of dust were taken up within the atmosphere and transported across much of the globe. Considerable deposits of this material, known as loess (in excess of tens of metres thick), were laid over large regions of continental interiors. The material was also deposited on the ocean. Some scientists argue that the production of plankton in the oceans was enhanced during the ice age by "iron fertilization" caused by dust deposition in the ocean. If this was the case, it may provide one of the processes by which atmospheric CO_2 is down-drawn during ice ages (although a relationship between CO_2 and air temperature has been established, the mechanisms by which CO_2 is taken or supplied to the atmosphere remain to be identified fully over glacial cycles).

The physical environment of LGM Earth had huge consequences for the distribution of plants and animals. In fact the study of plant material (such as pollen) and animal remains (such as whalebones) are critical to our understanding of ice age conditions. At the edges of formerly glaciated environments, such as the United Kingdom, ancient polar fauna and flora have subsequently been replaced by a deciduous biome. A similar story can be told for the oceans; where once cold-water plants and animals were abundant, now warmer-water varieties thrive.

The ice age also witnessed the rise to dominance of *Homo sapiens*. The oldest fossilised evidence for *Homo sapiens* is from about 130,000 years ago. Consequently the development of their population, as well as the decline of *Homo neanderthalensis,* took place during the last ice age. It is interesting to note that modern human development was able to survive and indeed thrive over a considerable period of environmental change. It is also important to acknowledge that the establishment of modern civilisation has taken place over just the last 10,000 years, during which time Earth's climate has been atypically stable.

An interesting feature of ice age Earth is that, as sea level was much lower, land bridges occurred between regions now separated by shallow sea. Importantly, such a connection was made across the Bering Strait, which, during deglaciation as the Laurentide and Cordillern ice sheets began to melt, may have encouraged humans to cross from Asia and populate the American continent.

Between the LGM and the end of the ice age, the return to the relative warmth of the modern world was punctuated by short episodes of climate cooling. The most significant of such climate reversals is known as the Younger Dryas (named after a tundral flower found in ancient sediment across several sites in northern Europe), which saw regrowth of glaciers across many parts of the Northern Hemisphere for a period of about 1000 years. The exact cause of the Younger Dryas is not well understood, but many believe it was a consequence of a shut down in the ocean flow caused by desalination of the North Atlantic by Laurentide iceberg melt. If so, the cooling would have been a phenomenon that was restricted spatially. However, some argue for evidence of the Younger Dryas across the Southern Hemisphere. Much work remains to be done in pinning down the spatial magnitude and cause of the Younger Dryas. Such work would be vital to understanding the nature of connections between processes affecting the climate of both hemispheres.

During the seventeenth, eighteenth, and nineteenth centuries air temperatures were a few degrees cooler than today, causing the widespread growth of many glaciers. This period is known as the Little Ice Age (LIA), and is characterised in history by "frost fairs" on the ice-capped River Thames in winter and in literature by a Dickensian view of Christmas weather perpetuating in Christmas cards the world over. Seldom, however, in the twentieth century did London experience snow on 25th December. Consequently the LIA was a period of rapid short-term climate change. The exact cause of the LIA is not well understood. There are several processes that theoretically can act over a period of a few hundred years, such as solar activity (not to be confused with orbital variations) and ocean circulation change. Although one of these is likely to be responsible for the LIA, much work still needs to be done to fully comprehend this climate phenomenon.

MARTIN J. SIEGERT

See also **Antarctic Ice Sheet: Definitions and Description; Filchner-Ronne Ice Shelf; Glacial Geology; Ice Chemistry; Ice Sheet Modeling; Isotopes in Ice; Ross Ice Shelf; Thermohaline and Wind-Driven Circulations in the Southern Ocean**

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ICE–ATMOSPHERE INTERACTION AND NEAR-SURFACE PROCESSES

The climate of the Antarctic continent is famed and feared for its harshness. Being almost entirely covered by ice and snow, Antarctica is not only the coldest place on Earth, with temperatures down to 90°C below the freezing point of water, but also the windiest. With annual mean wind speeds in some coastal places reaching almost 20 m s^{-1}, it was aptly coined "The home of the blizzard" by Australian explorer Douglas Mawson nearly a century ago. It is the combination of intense cold and fierce winds that makes Antarctica such an inhospitable place for humans.

The extremely low temperatures over Antarctica are due mainly to its topography (elevations over 4 kilometers in the center) and its isolated location at the South Pole. The strong surface winds are less easily explained, however. Whereas stormy winds in the rest of the world usually arise from highly variable large-scale weather systems and synoptic pressure gradients, in Antarctica they are strongly tied to near-surface processes. Surface winds in Antarctica are not only very strong, but also very persistent in terms of direction. These winds are called katabatic winds, and originate because of intense cooling over a sloping ice surface.

Most of Antarctica is covered by a huge ice sheet. Ice itself is a deformable medium, and hence it slowly flows from the high inland towards the coast. The ice mechanics associated with this flow induce a parabolic ice surface profile, with steep outer edges and a vast central plateau exhibiting little inclination. Since katabatic winds are proportional to surface slope—the steeper, the stronger—it is not surprising to find that the coastal escarpments experience the fiercest katabatic winds.

The Katabatic Wind Pump

Katabatic winds are ultimately caused by surface air that becomes colder than the air higher up in the boundary layer. On an inclined surface this means that the air at a particular location is colder—and hence, heavier—than the air at the same elevation downslope. Gravity then forces this cold air to flow downward, and this process continues as long as the surface air is cooled. In Antarctica, this cooling goes on semipermanently, and that is why the katabatic winds only rarely cease.

The snow surface, reflecting most of the incoming sunlight because of its brightness, experiences a strong radiation deficit. More infrared or thermal radiation is emitted than solar radiation absorbed, causing the temperature of the snow surface to drop. With the surface temperature being lower than that of the overlying air, the near-surface air is stably stratified (densest near the surface, less dense higher up). This means that turbulent motions in the surface air layer will transport heat from the atmosphere towards the surface. This flux of heat eventually balances the radiation deficit of the surface, but it also cools the surface air and as such motors the katabatic flow.

Interestingly, the downward heat transport is strongly dependent on wind speed (the stronger the wind, the higher the heat transport) but also on the magnitude of the vertical temperature gradient. This temperature gradient, in turn, depends heavily on wind mixing: in stormy conditions, mixing is strong and the atmosphere will be less stably stratified. Under still conditions, mixing is virtually absent, and the surface will be much colder than the overlying air. All taken together, this means that the katabatic wind system is based on an intricate balance between surface cooling, katabatic wind forcing, and wind mixing. The coastal regions with the steepest surface slope generally experience the strongest katabatic winds. Being deflected by the Coriolis force, these katabatic winds generally blow from southeasterly directions and are strongest in winter when surface cooling is most severe.

The Surface Mass Balance

The Antarctic Ice Sheet gains ice mass through snow accumulation. Most snow falls in the coastal regions, whereas the high inland regions are as dry as a desert with only 5 cm of snow accumulation per year. There, annual precipitation occurs in a few events, when synoptic low-pressure systems manage to battle themselves onto the high plateau. Moreover, air can hold significantly less moisture when it gets colder, so when it encounters the deep-freeze conditions of the Antarctic inland most moisture has already been squeezed out.

Generally, mass loss at the surface of an ice sheet occurs through melt, sublimation and, on the local scale, wind erosion. Surface melt takes place only in some isolated coastal locations and on the Antarctic Peninsula where summer surface temperatures regularly exceed the freezing point, but averaged over the Antarctic continent, melt is insignificant. On the other hand, sublimation, the phase transition from the solid snow directly to water vapor, occurs everywhere but depends strongly on wind speed and temperature, and amounts on average to about 10% of the total accumulated snow.

The sum of all water mass fluxes to and from the snow surface is generally referred to as the surface mass balance. When positive, the surface gains mass on an annual basis because snowfall is abundant, for instance. In mild, low-lying glaciated regions, significant melting may exceed snowfall resulting in a negative surface mass balance. Over the Antarctic Ice Sheet, the surface mass balance is positive nearly everywhere. Moreover, it peaks in the coastal regions because of the precipitation distribution. In the inland reaches, the mass balance is slightly positive because of the extreme cold, causing melt to be absent and sublimation to be minimal.

The transport of snow by the winds is probably only of secondary importance to the overall mass balance of Antarctica. An interesting aspect of the persistent near-surface katabatic winds of Antarctica is that they are able to carry huge amounts of loose snow over great distances. The amount of snow transported by the wind—also known as drifting snow, or blowing snow—increases dramatically with wind speed. Hence, the strong katabatic winds are able to redistribute large amounts of the precipitated snow, with erosion and deposition patterns being largely governed by the ice sheet topography.

Blue Ice Areas

An illustrative example of the local effects induced by erosion and deposition of drifting snow is the existence of so-called blue ice areas. These are very localized regions, usually only a few square kilometers in area, where the topography has induced a surface wind field that favored continuous erosion of snow, leaving bare (blue) ice. Usually, but not exclusively, these blue ice areas are found in the wake of mountains protruding through the ice surface. Over the course of time, strong, turbulent surface winds have eroded the entire snow deck. Once the ice layer has surfaced, snow was unable to stick to the smooth ice, preventing the blue ice area from being covered by snow again.

The persistence of blue ice areas is reinforced by strong sublimation rates. Since blue ice is darker than the adjacent snow fields, heating through solar radiation is more vigorous, creating a relatively mild local climate in which the ice surface loses mass through surface sublimation. While only a tiny fraction of Antarctica is covered by blue ice, its bluish appearance makes it fairly easily recognizable from space. If climate-induced changes in temperature and wind somehow affect the size of blue ice areas, these regions may be used as an indicator of climate variations taking place over the southern continent.

Drifting and Blowing Snow

Because of the ever-persisting katabatic winds raging down Antarctica's icy slopes, blizzards, snow storms, and drifting and blowing snow are very common phenomena. Since loose surface snow is found almost everywhere on Antarctica, surface winds over about 7 m s^{-1} inevitably cause surface snow particles to become airborne. At moderate winds, individual snow particles bounce along the surface—a process called saltation—thereby ejecting more particles. When wind speeds increase further, the particles become fully detached from the surface and start to float. This state of snowdrift is usually referred to as suspension. Driven by Antarctica's persisting katabatic winds, snow particles may travel tens to hundreds of kilometers before settling down again.

Like surface snow, however, suspended snow particles are continuously subject to sublimation. Traveling downslope with the katabatic wind, turbulent updrafts are required to keep the particles afloat. These induce a turbulent moisture flux, or sublimation, which eats away mass from the particle. Snowdrift sublimation is a relative efficient process, since snowdrifting particles are surrounded by air on all sides (in contrast to particles at the surface). Hence, this constitutes another, two-step, mechanism by which the snow surface loses mass: first snow particles are swept up by the winds, after which they are slowly sublimated away. Calculations have shown that, averaged over the entire continent, surface and snowdrift sublimation may be of equal importance in removing mass from Antarctica's surface.

Over most of Antarctica's vast ice sheet, snow is deposited quite infrequently during a few precipitation events per year, indicating that the snow layering is equally irregular. Erosion of snow at one particular location and deposition of the same snow elsewhere adds to the potential confusion when studying snow layers. Even though researchers have been able to recover annual layers from most sites, they must always consider the possible disturbing effects of drifting snow.

Snow Density and Snow Dunes

Generally, freshly fallen snow has a density of about 100–150 kg m^{-3} (the density of solid ice is 920 kg m^{-3}). On Antarctica, however, the density of surface snow is as high as 300–400 kg m^{-3}. The main cause of the high surface density is the action of the surface winds. During snowdrifting conditions, individual particles collide, break, and generally become more round. Starting as snow flakes, they quickly turn into much smaller, rounded particles which can be more densely stacked. This process is referred to as wind packing. Another reason for the densification is the metamorphosis by sublimation after snow is fallen on the surface, a process known as aging.

Readily recognizable features of the Antarctic surface are the snow dunes, or sastrugi. They occur virtually everywhere over the continent, though their size ranges considerably from place to place (sastrugi up to one meter in height have been reported). Their ultimate cause is the wind, sweeping up loose snow particles in a quasi-regular fashion. Extended areas of sastrugi have been found to severely obstruct land-based transport, for instance when using snowmobiles. Elongated mega snow dune systems, not unlike the patterns seen in subtropical sand deserts, have been observed from space. As it turns out, the transport of snow by the wind resembles the sand transport very closely, and the existence of snow dunes is a clear manifestation of that.

Outlook

It is clear that the specific surface climatic conditions of the Antarctic are causing phenomena not seen elsewhere on Earth. Antarctica's meteorological conditions, snow texture, and glaciological features are currently being scrutinized through ground-based fieldwork, by satellites and using numerical modeling. It is anticipated that the combination of these approaches will eventually lead to the solution of the many riddles that Antarctica still holds today.

Richard Bintanja

See also **Air-Borne Ice; Antarctic Ice Sheet: Definitions and Description; CryoSat; Firn Compaction; Ice Core Analysis and Dating Techniques; Ice Sheet Mass Balance; ICESat; Mega-Dunes; Precipitation; Snow Post-Depositational Processes; Surface Energy Balance; Surface Features; Surface Mass Balance; Wind**

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ICE CHEMISTRY

Most of the ice in the Antarctic Ice Sheet is extremely pure. However, along with the water molecules, there are traces of chemicals, which give the ice many of its physical properties. There are also small bubbles of trapped air containing atmospheric gases. Because concentrations are generally very low, analysis of these chemicals is challenging, but is now very common in ice core laboratories worldwide. The changing concentrations of the chemicals, in both the ice and the air bubbles, give an excellent indication of the past content of the atmosphere. By drilling ice cores from the Antarctic Ice Sheet, scientists have been able to reconstruct the climate of the Antarctic, and the concentrations of atmospheric gases and particles, over time periods up to 800,000 years.

The Chemical Content of Antarctic Ice

The past temperature of the Antarctic is derived from measurements of the isotopic content of the water molecules themselves. However, all the other information derives from the small amounts of added impurities, which come from the atmosphere through long-range transport and mixing.

Various sources contribute to the chemical content of the ice. In coastal regions, material derived from sea salt is often dominant. Recent work suggests that the sea ice surface, as well as open water, is a source for this sea salt component. Another major impurity that comes from the ocean is sulfur-based ions: sulfate and methanesulfonate (MSA). Both these ions are the products of atmospheric oxidation of another compound (dimethylsulfide) which is emitted by marine algae. The concentration of sea salt in particular falls off rapidly from the coast towards inland areas of Antarctica.

Sulfate can also come from volcanic activity. In particular, after major eruptive volcanic activity, sulfur dioxide reaches the stratosphere and falls over the whole Earth (including the ice sheets) over a period of generally 2–3 years. This is detected as a high spike of sulfate in an ice core, and these spikes are very useful for synchronising different ice cores to each other and to known volcanic eruption dates.

Despite the very large distance across the Southern Ocean, small amounts of terrestrial dust reach Antarctica, and can be identified either by measuring the insoluble dust or by measuring ions or metals (such as aluminium) that are primarily associated with terrestrial dust. Geochemical analysis of such dust has indicated that South America is a particularly important source of dust to Antarctic ice.

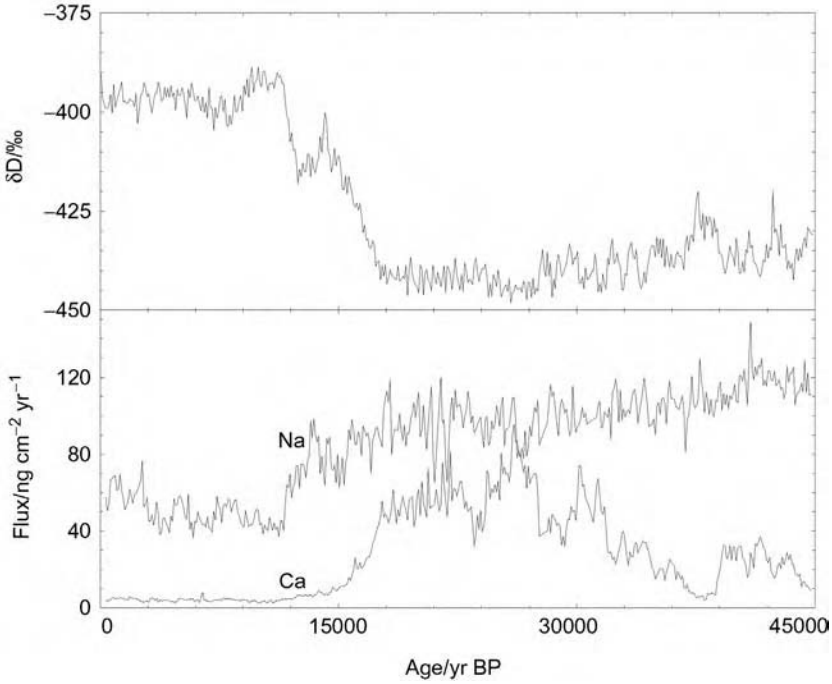
Other chemical material also reaches the ice—for example nitrate, which probably comes from the upper troposphere or lower stratosphere; small amounts of organic material; and even tiny amounts of pollutants such as lead from vehicle exhausts.

In addition to the chemicals trapped in snow, samples of the atmosphere are isolated into the tiny air bubbles that form when the snow turns to solid. Within these bubbles are found all the stable gases from the atmosphere: nitrogen and oxygen, but also greenhouse gases such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). In deeper ice (below several hundred metres depth) the air bubbles form air hydrates—separate crystals of gas molecules caged by water molecules. However, the air from these hydrates can also be extracted and analysed in the same way as that from the bubbles.

There is still some discussion about the way in which the nongaseous impurities are included in the ice. In laboratory experiments, ice is able to exclude most impurities from its lattice, pushing them into the grain boundaries. In nature, this could occur on formation of the ice, or during subsequent movement of grain boundaries through the ice. A few compounds are expected, on both theoretical grounds and experimental evidence, to be included in the lattice: for example hydrochloric acid (HCl) and ammonium hydroxide can sit in the ice lattice and take part in hydrogen bonding within it. There is clear experimental evidence that, in some circumstances, impurities are indeed excluded, both to the grain boundaries (where two grains meet) and to triple junctions (where three grains meet). In the latter case, veins of impurity can be present that have liquidlike properties even at temperatures as low as –70°C. However, there is also evidence that, under some circumstances, impurity is held in inclusions within the crystals themselves. Whatever the microphysical location, ice chemistry is generally conserved through time, and apart from some minor diffusion, immobile.

Impurities play a decisive role in determining the electrical properties of ice, the growth of ice grains, and possibly the mechanical flow properties of the ice. In the case of the electrical properties, while pure ice has a small direct current (dc), and larger high frequency conductivity, this is generally overwhelmed by an additional conductivity due to ionic impurities. This forms the basis of two common techniques of analysis that can be carried out on solid ice, electrical conductivity analysis (ECM) and dielectric profiling (DEP). For example, large increases in conductivity are seen across volcanic eruption horizons, due to the high concentration of sulphuric acid in the ice.

Impurities with a significant vapour pressure are not entirely fixed in the upper snowpack, and some of



Antarctic ice core chemistry over the last 45,000 years from the European Project for Ice Coring in Antarctica (EPICA) Dome C core (Röthlisberger et al. 2002). The top panel shows deuterium, representing temperature, with the transition from the last glacial maximum (LGM), c. 20,000 years ago, to the warm Holocene period. In the lower panel, both sodium (Na, top line, representing sea salt) and especially calcium (Ca, lower line, representing terrestrial material) were at much higher concentrations in the LGM.

them can be reemitted as the temperature and snow surface area changes, or can be photolysed in the upper few cm of snow. At some sites the emission of chemicals from the snowpack can have a significant effect on concentrations of chemicals in the lower atmosphere. For example, photolysis of nitrate from snow seems to control the concentrations of NO_x (NO + NO_2) in the Antarctic ice surface/atmosphere boundary layer at many sites, with significant further effects.

Ice Chemistry Sampling and Analysis

A wide range of chemical analyses is carried out on ice cores. For the impurities in the ice itself, the ice may be cut (using a bandsaw) into individual depth increments, and then analysed. The method of ion chromatography has been very widely used to measure the major ionic impurities such as sodium, calcium, chloride, nitrate, and sulfate. Insoluble dust has frequently been measured by particle counting techniques, such as the Coulter Counter or laser optical methods. Metals and isotopes of them have been measured by various techniques, with inductively coupled plasma-mass spectrometry (ICP-MS) most often favoured in recent years. For all these methods, strong precautions against contamination must be taken, and the use of clean air laboratories and particle-free clothing and gloves is often necessary. As an example, although concentrations of lead have increased in Antarctic ice since preindustrial times, they remain about 1/1000 of the levels found in typical European tap water, so it is very easy to contaminate samples unless precautions are taken. Because the outside of ice cores is often very dirty, due to contact with drills and drilling fluids, it must normally be removed before sampling and analysis is attempted.

New methods of sampling and analysis have come to the fore. These generally involve melting strips of ice core on a hot plate. The outer, contaminated parts of the core are melted into an outer ring and drawn away for less sensitive analyses, while the inner, clean part can be directed through tubes to analysers. This procedure produces a stream of melt that can be sampled regularly or continuously, and it decontaminates the ice as part of the process. In early realisations of this method, known as continuous flow analysis (CFA), the water was directed to various streams where absorption or fluorimetric methods were used to analyse for compounds such as hydrogen peroxide and formaldehyde, as well as metals such as calcium and sodium. In some laboratories, CFA melters are now also used to provide sample streams for fast ion-chromatographic methods and mass spectrometers, and for discrete sampling to clean containers.

Ice Core Chemical Records

A wide range of ice core chemicals has been measured, covering timescales from seasonal up to 800,000 years. Over shorter timescales, records of recent decades have revealed whether pollution reaches Antarctica, even in small quantities. Variations over years to centuries have been linked to modes of atmospheric circulation, and offer the possibility of reconstructing such modes back into the preinstrumental period. Over longer periods, chemicals in the ice vary strongly between warm "interglacial" periods (such as the Holocene, the last 10,000 years of relative warmth), and cold "glacial" periods.

The concentrations of most chemicals vary strongly with the seasons. For example, the marine biogenic component (MSA and part of the sulfate) peaks in the summer period of marine productivity, while sea salt peaks in the winter half-year. Concentrations also vary from year to year, presumably as a result of a combination of changing source strength and atmospheric transport. Several authors have made links between concentrations of chemical components at various ice core sites and meteorological parameters such as the strength and location of atmospheric pressure features, the passage of the Antarctic circumpolar wave, and the amount of sea ice present. The patterns are complex, and more work, at more sites, is needed to establish these methods on a firm enough footing to derive these parameters in the past.

Over recent decades, emissions resulting from human activities have affected most of the Earth's atmosphere. However, no clear increasing trend in concentration can yet be seen in Antarctic snow for chemicals such as nitrate and sulfate that are now predominantly anthropogenic even in Greenland. A clear exception to this is the case of lead. Profiles of lead in snow and ice over the last century show that its concentration increased by at least a factor 5 over the natural level between the nineteenth century and the 1980s. This was first due to metal production activities and then the use of leaded gasoline in countries of the southern hemisphere. It parallels (but in a much weaker form) similar trends seen in Greenland (Northern Hemisphere) records. Concentrations have decreased in the last two decades, as unleaded fuels have been introduced.

The greenhouse gases provide the clearest example of an anthropogenic effect seen from Antarctic ice cores. Antarctic ice cores have shown that the CO_2 concentration has increased from about 280 ppmv (parts per million by volume) in 1800 to its present value above 370 ppmv. Methane concentrations have nearly doubled in the same time. On glacial–interglacial timescales, the greenhouse gases vary naturally with climate.

The spikes of sulphuric acid in the ice have been documented and compiled to give inventories of the past strength and numbers of volcanic eruptions. Whilst it is difficult to compile an accurate inventory from a single core, combining several cores gives the best hope of deriving an objective volcanic index into the past—information which is needed to evaluate the effect of volcanic eruptions on climate. Attempts have also been made to use another chemical in the ice, ^{10}Be, to derive an index of solar activity—another essential forcing factor for climate change.

Most of the major chemical components in the ice also vary in concentration dramatically with climate. Over the last 800,000 years, the Earth's climate has varied with a period close to 100,000 years; in the latter part of the record, the variation has consisted of short (10,000–30,000 year), warm interglacials and long, cold glacial periods. Most chemical concentrations are much lower during warm than cold periods. For example, the flux of insoluble dust to central East Antarctic ice was more than a factor 20 higher during the last glacial maximum (LGM, about 18,000 years ago) than in recent times. Fluxes of sea salt were about a factor 2 higher at the LGM than today. The cause of the increased dust concentration is probably a drier and windier climate in the source, most likely Patagonia, although a more vigorous transport could also have played a role. Dust concentrations in Antarctic ice can therefore give information about South American climate. The cause of the higher sea salt fluxes remains under discussion, but one idea is that the higher concentrations are a result of stronger sea ice production.

In summary, although Antarctic ice is rather pure, its chemical content has important physical effects, and the changing concentrations document changes with time in the Antarctic atmosphere. Ice core chemistry, in combination with ice core isotopic and gas measurements, provides the most powerful possible tool for evaluating past changes in the atmosphere, and their interactions with climate.

Eric Wolff

See also **Air Hydrates in Ice; Antarctic Ice Sheet: Definitions and Description; Atmospheric Gas Concentrations from Air Bubbles; Climate; Climate Change; Earth System, Antarctica as Part of; Firn Compaction; Ice Ages; Ice–Atmosphere Interaction and Near Surface**

Processes; Ice Core Analysis and Dating Techniques; Isotopes in Ice; Lake Ellsworth; Lake Vostok; Paleoclimatology; Pollution Level Detection from Antarctic Snow and Ice; Precipitation; Sea Ice, Weather, and Climate; Snow Biogenic Processes; Snow Chemistry; Snow Post-Depositional Processes; Temperature; Volcanic Events; Volcanoes; Wind

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ICE CORE ANALYSIS AND DATING TECHNIQUES

Ice cores are an immensely powerful tool for determining past climatic and environmental conditions. However, they are a challenge for analysts, because it is generally necessary to process large numbers of samples, using as little ice as possible, and at low concentrations of many analytes. It is also crucial to date ice cores correctly and to be able to synchronise them with other paleoclimate records.

Processing and Physical Analysis

A huge range of physical and chemical analyses is made on the most important ice cores. The first step is the initial processing of the cores, which often includes some physical analysis, as well as sectioning of ice for different analyses. In some cases, this processing is carried out at the field site, in others at home laboratories.

Because ice cores are drilled in discrete lengths, of at most a few metres each, the first process to occur after drilling has to be logging—marking the cores for length and orientation, and fitting each core to the previous one to establish the continuous sequence.

Dielectric profiling (DEP) measures the capacitance and conductance of ice at a range of frequencies. Curved electrodes on either side of the core are connected to a commercial measuring device. From the measurements, the high-frequency permittivity (related to density), and conductivity (related to chemical content) can be determined. Either a sequence of electrodes or a moving electrode is employed to make measurements at a resolution of mm to cm. The conductivity data show the depths where major changes in chemistry (e.g., volcanic eruption material) occur, allowing alterations in the subsequent sampling strategy. A related technique, the electrical conductivity measurement (ECM), is carried out at direct current frequencies, and measures the current between a pair of electrodes (with typically 1 kV between them) dragged along an ice surface. A fresh ice surface is preferred, and so ECM is normally carried out after a cut has been made along the core length. ECM responds only to acidity in the ice core, and is used particularly to document volcanic acid input.

Other physical measurements have been made by running instruments along the length of cores. A line scanner or camera can record the optical properties of ice. This documents the presence of air bubbles, of visible ash layers (from volcanic tephra) and of so-called cloudy bands: bands of milky ice, normally associated with high impurity content. Cloudy bands apparently occur at annual spacing in ice from the last glacial period in Greenland, and can be used to assist annual layer counting for dating.

Thin sections of ice, prepared with a microtome, are required for measurement of crystal size, shape, and fabric. These point to the deformation and grain growth history of the ice, which in turn is controlled by the large scale flow and temperature history, as well as the intrinsic properties of the ice. Crystal fabrics are measured using crossed polarisers. Crystals with different orientations show up in different colours with this technique. Automatic mapping of the fabrics generates statistics about the ice structure. Deformation tests can also be made, to understand the mechanical properties of ice: if realistic stresses are applied they require months or years for each experiment, although extrapolation from shorter experiments is also carried out.

Stable Isotopes of Water and Cosmogenic Isotopes in Ice

The measurement to which most other ice core data are often keyed is that of the stable isotopes of water. The ratio of both $^{18}O/^{16}O$, and $^{2}H/^{1}H$ (^{2}H is deuterium, D) in water, although the result of complex processes in the hydrological cycle, is generally considered to be mainly a measure of the temperature at the time and place of snowfall. It is therefore a very useful paleoclimate proxy, and can sometimes also be used as a dating tool. Values are expressed as a difference ($\delta^{18}O$ or δD) from the ratio found in standard ocean water, in parts per thousand (‰). A derived property, the deuterium excess ($\delta D - 8*\delta^{18}O$), is related to properties at the ocean source, and obviously good precision in the measurement of the individual isotopes is mandatory if the excess is to be calculated accurately. The ratios are measured on small water samples using mass spectrometry after equilibration with CO_2 (for $\delta^{18}O$) or reduction to H_2 (for δD).

The isotope ^{10}Be is produced by interaction of cosmic rays with major atmospheric constituents. The production rate is determined by factors that shield the Earth from cosmic rays: the Earth's geomagnetic field strength and solar properties linked to solar activity. To measure ^{10}Be concentrations in ice, volumes of melted ice (typically 150 g with instruments available in 2005) are concentrated on an ion exchange resin, and after appropriate treatment, the ^{10}Be concentration is measured using accelerator mass spectrometry. This measurement requires a lot of ice, but is very useful, both in chronology and as an indicator of past solar activity.

Analysis of the Chemical Content of Ice

Although only low concentrations of ionic and other chemicals exist in ice, they can be used as indicators of numerous environmental parameters, such as sea ice conditions, past atmospheric transport, volcanism, and past biogenic activity. The major ionic impurities (Na^+, Mg^{2+}, K^+, Ca^{2+}, Cl^-, NO_3^-, SO_4^{2-}) are present at μg kg^{-1} (ppb) levels, and have traditionally been measured by ion chromatography (IC). Insoluble dust has been measured (both for concentration and size) using the Coulter Counter instrument. Samples must be cleaned before they are melted, to remove external contamination, particularly from drilling fluids.

In recent years, the traditional route of cutting individual samples of a few mL for such analyses has been partially superseded by methods (known generically as continuous flow analysis or CFA) in which a length of ice with square section (typically 3 cm $\times$ 3 cm) is placed vertically on a hot plate with concentric channels. The liquid from the central disc is automatically cleaned by this procedure and can be directed either to clean vials for IC analysis or to channels in which individual components are measured by using chemical reactions that produce a colorimetric response (absorption or fluorescence). This technique has been used very successfully for components such as Na^+ and Ca^{2+}, as well as ammonium and species not measured by IC, such as formaldehyde. Continuous flow methods in which light scattering is used to measure dust concentration have also been developed.

A range of other chemicals is measured less frequently in ice. Ultra-trace elements (including heavy metals such as lead [Pb]) are present only at ng kg^{-1} (ppt) levels, and require extreme precautions against contamination. Inductively coupled plasma-mass spectrometry (ICP-MS) has generally superseded other techniques for these elements, and in one laboratory, CFA has been coupled to ICP-MS. Organic and biological molecules are less commonly measured in ice cores, although they clearly have potential as rather specific markers of particular sources.

Finally, a range of isotopes of the chemical components in ice can be measured, although low concentrations make such measurements difficult. They are used to add information about the origin of material in the ice. For example, ^{34}S in SO_4^{2-} allows volcanic sulfate to be differentiated from that of marine origin, while the isotopes of Pb, Sr, and Nd can be used to fingerprint the geographical provenance of terrestrial dust. Mass spectrometry, using a range of preparation and introduction techniques, is the measurement method.

Analysis of Gases in Ice

When snow is compressed to form solid ice, air bubbles are trapped, and these act as a sample of all the stable components of air. Although the bubbles subsequently convert into air hydrates under pressure at depth, these too can be recovered to allow analysis of the gas content of the ice, and hence of the past atmosphere. For some insoluble gases, such as methane (CH_4), a simple wet extraction can be employed, but for more soluble gases (such as carbon dioxide, CO_2), it is necessary to use a dry method: either crushing or sublimation. In the crushing method, the ice is placed in a container, which is evacuated, and the ice is then crushed or milled into pieces sufficiently small that all the air can be removed. The resulting gas samples can be analysed for a whole range of atmospheric constituents, as well as for their isotopic ratios.

CO_2 is analysed either by infrared laser spectroscopy or gas chromatography. Mass spectrometry is the method of choice for most of the other gas measurements. CH_4 and N_2O (nitrous oxide) are other greenhouse gases that are determined. ^{13}C in CO_2 and CH_4 is now measured as a way of understanding changing sources and sinks. ^{18}O in the oxygen content of the air (as opposed to that in water, discussed previously) is another important analyte, bringing information that is extremely important for linking ice core and marine sediment records, since the ^{18}O content of both is partly controlled by global ice volume. The total air content of the ice is to first order controlled by the atmospheric pressure, and hence the altitude of the ice sheet. Finally, trace gases at even lower concentrations (such as halocarbons) are now routinely measured in columns of firn air (where large volumes of air are available), and are starting to be measured in gas bubbles below the firn.

Dating Techniques

Accurate dating is essential for comparisons between records, and for understanding the controls on regular periodic climate variations. At sites with high snow accumulation rates, annual layer counting may be possible. Many markers in the ice (including $\delta^{18}O$ and often dust and ionic impurities) vary seasonally, providing records that can be counted. Poor core quality or hiatuses in snow accumulation certainly limit the possible accuracy of such layer counting. Not all markers reliably have one peak per year: for this reason, counting using multiple proxies is strongly recommended. Under good conditions, it has been suggested that counting to a precision of around 1% may be possible in the Holocene period (last 10 kyr, 1 kyr = 1000 years), although the precision is certainly reduced in older ice.

Such counting can be checked by the use of fixed markers of known age. For example, peaks of beta-radioactivity are always found in snow from 1964 due to the large amount of atmospheric nuclear bomb tests carried out in the preceding year. Peaks in sulfate (also reflected in the ECM and DEP) are found in years when large volcanic eruptions took place, such as 1815 (Tambora), 1883 (Krakatoa) and a sequence of peaks around 1259 AD (unknown volcano). In earlier periods, profiles of volcanic spikes can be matched between cores to synchronise them, although the exact dates of each eruption are unknown.

A new method to date ice from the last 10 kyr has recently been developed. The production of ^{10}Be (see previous discussion) is controlled by the same factors as that of ^{14}C, which is measured in annually dated tree rings. After appropriate modelling, it is possible to match the small multidecadal wiggles in ^{10}Be in ice with the residuals around the trend of ^{14}C in tree rings, in order to tie ice cores to the dendrochronological scale.

For sites with low snow accumulation rate and for older ice, annual layer counting is not possible. Most commonly these cores are dated using a glaciological flow model. Because ice flow (and thinning of layers) follows simple physical laws, the age can be modelled using a thinning function provided we know how the snow accumulation rate has varied with time. This can also be estimated using a simple model that relates snow accumulation to site temperature through vapour pressure. The free parameters in the model can be estimated if we have a few points at which the age is known. For example, a peak in ^{10}Be flux, found in all ice cores at around 41 kyr before present (BP), is believed to be related to a magnetic change which has been radiometrically dated in other sediments. Such ice flow models have been used to date most of the major deep ice cores. The greatest limit to such age scales is probably that they assume that the ice flow has been steady with time, an assumption that appears to have been violated in some cases.

These methods give an age scale for the ice, but the air bubbles in the ice have a younger age (because at the depth where they close off, typically 80 m, the ice is decades to centuries old, while the air is much younger). Determining the difference between these two ages is critical for determining the phasing between, for example, changes in temperature and changes in CO_2 concentration. Modelling of firn properties and the air enclosure process is used to do this.

The age scales of different cores can be tied together using properties that must change simultaneously at different sites. For the gas age scales, rapid changes in methane concentration are particularly effective for this purpose. Methane has a short mixing time in the atmosphere compared to its lifetime, so even Greenland and Antarctic cores can be tied together when fast (decadal-scale) changes occur, as they did several times during the last glacial period. For ice age scales, volcanic eruption signals are excellent synchronisers, provided one can be sure that the same eruption is sampled in both cores. Synchronisation can be used to transfer a timescale from a well-dated high accumulation rate core to less well-dated cores from low accumulation rate sites. In the long term, it may be possible to link together a whole series of cores, and to provide a common timescale constructed from the best information available from all of them, although such a project has not yet been realised.

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See also **Air-Borne Ice; Air Hydrates in Ice; Antarctic Ice Sheet: Definitions and Description; Atmospheric Gas Concentrations from Air Bubbles; Climate; Climate Change; Earth System, Antarctica as Part of; Firn Compaction; Ice Ages; Ice–Atmosphere Interaction and Near Surface Processes; Ice Chemistry; Ice Sheet Mass Balance; Isotopes in Ice; Paleoclimatology; Pollution Level Detection from Antarctic Snow and Ice; Precipitation; Snow Biogenic Processes; Snow Chemistry; Snow Post-Depositional Processes; Volcanic Events; Volcanoes**

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ICE CRYSTAL SIZE AND ORIENTATION

A glacier is made up of small crystals that form during the compaction near the ice sheet surface, of snow into ice. The ice crystal size (typically $\sim$1 mm) near the surface is related to the size of the snow flakes at deposition, which in turn is related to air temperature, and the crystals are randomly oriented. In the upper layers (the top few tens to hundreds of metres in the Antarctic Ice Sheet), the ice crystals grow at a temperature-dependent rate.

Deeper, where the ice begins to flow because of the stresses imposed on it by gravity (i.e., by the weight of the ice itself), the size and orientation of the crystals begin to change in response to the flow. The higher the flow rate, the smaller the ice crystals will become. Furthermore the crystals begin to align in particular directions related to the stress configuration. Throughout most of the deeper ice in Antarctica, where the ice is in shear approximately parallel to the bed, the crystals align so that the crystal glide planes are parallel to the flow direction. The optical or c-axis of an ice crystal is perpendicular to the glide plane. Thus in the ice sheet deep layers, the c-axes all tend to be near vertical. By examining ice thin sections mounted between crossed polaroid filters one can measure crystal size and orientation. Each crystal appears as a different colour due to its orientation, and using a universal stage, the orientation of individual crystals can be measured. A map, or fabric diagram, of the crystal orientations is then drawn. In glaciology, a microscope is not required to see the crystals, which are much larger than those of most other minerals, and a larger universal stage is used, usually referred to as a Rigsby stage.

A feedback mechanism operates between the crystal fabric pattern and the ice flow. While the ice flow under different stress patterns generates different crystal orientation patterns, so too does the fabric pattern affect the ice flow rate. For example, ice with a strong vertical crystal orientation fabric pattern in near horizontal (bed-parallel) shear will flow as much as ten times faster than ice with a random crystal orientation pattern. Thus, an understanding of the crystal structure of the ice and an understanding of the physics of how ice flows is essential if accurate models are to be developed of the Antarctic Ice Sheet, and if accurate estimates are to be made of changes in the size and shape of the Antarctic Ice Sheet.

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See also **Antarctic Ice Sheet: Definitions and Description; Firn Compaction; Glaciers and Ice Streams; Ice Sheet Modeling; Snow Post-Depositional Processes**

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ICE DISTURBANCE AND COLONISATION

Marine life on the Antarctic coast, and also in the Arctic, is vulnerable to ice disturbance from the shore line to as deep as 550 m water depth. Icebergs produced by calving from glaciers, fast ice that forms on the sea surface, and anchor ice that crystallizes on the sea bed are all hazards to benthic (bottom-living) organisms, especially those that are sedentary. Yet this disturbance also provides niches for hiding, new surfaces to graze on, release from competition, and space for colonization.

Fast Ice

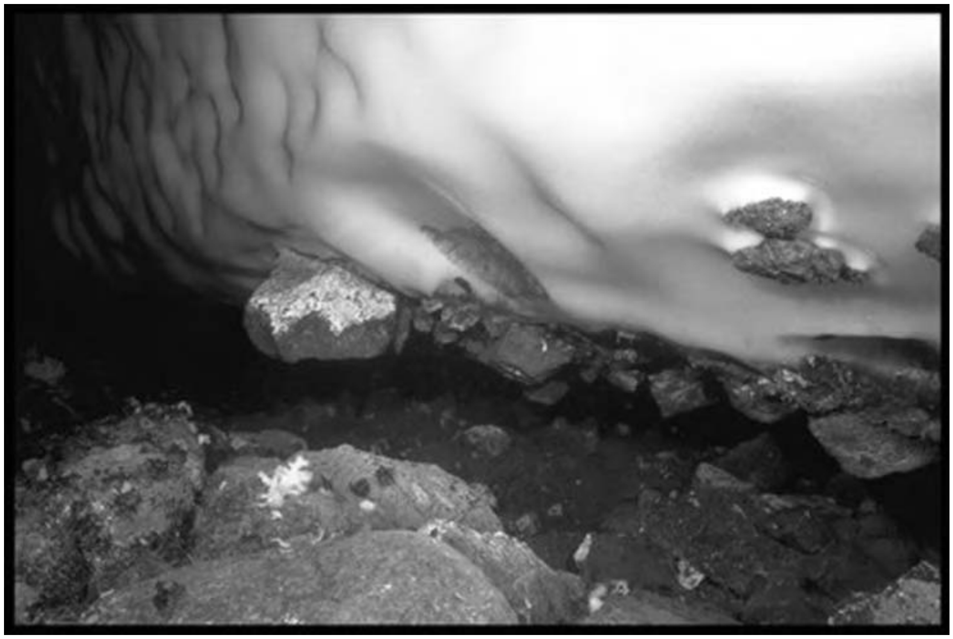
Where ice on the surface of the ocean meets the shore, it attaches to the land as fast ice. When this happens, the shoreline frozen to the fast ice becomes unavailable to marine life. Additionally, more shoreline is scoured by ice moving with the waves and currents when the fast ice breaks up in the summer. Fast ice can also affect seabed at a distance. As the ice forms on the surface of the ocean in the fall, salt from the sea water is captured between the ice crystals. The salt is excreted over the winter as concentrated brine which, being heavier than seawater, sinks to the seafloor. The brine collects in seafloor depressions, such as those created by ice scour, where it kills animals and algae living on the seafloor or burrowing underneath. The dead organisms decompose, in the process using up the oxygen in the brine pools. The lack of oxygen results in the pools becoming high in sulfur and iron, giving them an odour and a black colour. These "black pools of death" then become lethal traps for shrimps and fish that may blunder in. First discovered in the Arctic, black pool formation can occur in coves and inlets in the Antarctic wherever water movement is limited. Fast ice also has positive impacts, however. It provides a winter habitat for a diversity of microbes and ice algae which feed krill and fish. In the spring, small photosynthetic organisms called diatoms grow on the undersurface of the fast ice, attracting more grazers. When the ice breaks up in the summer, the diatoms fall to the seafloor, where they then become food for the bottom fauna.

Ice Foot

Fast ice can extend several meters below shore in the shape of a foot. This ice foot can persist for much of the year and limit accessibility of the shore to the short summer when it is not present. Then, fast growing algae and diatoms colonize the shore, giving it a grassy, green-brown appearance. This attracts motile grazers such as the limpet *(Nacella concinna)* and amphipods (small shrimplike crustaceans). Once the sea surface refreezes, the diatoms disappear, the grazers move deeper, and the ice foot forms again.

Anchor Ice

Where seawater is supercooled (cooled below its freezing point), as occurs in McMurdo Sound close to the Ross Ice Shelf, large plates of ice form, anchoring to the fast ice, ice foot, and seabed, and covering the seabed to as much as 30 m water depth. When this anchor ice accumulates to the point that it becomes too buoyant to remain attached, it can rip off grazing



Undersurface of a grounded iceberg in McMurdo Sound showing the vulnerable marine life. Boulders frozen into the iceberg can be lifted and carried thousands of kilometres, leaving evidence of past ice movements. (Photograph by Kathleen E. Conlan, copyright 1997, Canadian Museum of Nature.)

or ice-trapped organisms. Sea urchins and sea stars are attracted to the anchor ice, grazing on the diatoms that grow on the plates. Once the anchor ice lifts off, small opportunistic animals, which reproduce rapidly and in large numbers, quickly invade the cleared space, burrowing into the sediment to eat detritus and diatoms. Anchor ice spreads along the coast over the winter and recedes as the water slightly warms in summer. The extent of anchor ice formation is influenced by climate and currents, even El Niño–Southern Oscillation (ENSO) events that originate thousands of kilometres to the north. Low anchor-ice years enable the fast growing bush sponge and its sea star predators to invade. Thus, anchor ice, like other disturbances, produces destruction for some but opportunity for others.

Ice Scour

Ice scour in very shallow water can occur many times within a year, but it can be very patchy and rapidly decreases in frequency with depth. Icebergs (ice calved off glaciers and ice shelves) can have deep drafts underwater, some reaching the seabed as deep as 550 m underwater when they turn over. Pressure ridges, formed by drifting pack ice pressing against shore-frozen ice, also send ice keels underwater. Combined, these icebergs and pressure ridges can scour paths up to 350 m wide, 15 m deep, and 15 km long over the surface of the seafloor. About 1.5 million km^2 of Antarctic seabed is vulnerable to being bulldozed, deformed, and resuspended by these ice keels. Physical consequences of ice scour are long-term changes to the seabed and (in the Arctic) damage of seafloor structures such as cables, wellheads, and pipelines. Biological consequences are destruction of communities of algae and animals, loss of biodiversity, and changes in community composition. In the Weddell Sea, where the original community is dominated by giant volcano sponges, the scours may take centuries to fully recolonize. These sponges provide many hiding and attachment places for other animals, which cannot return until the sponges recolonize and grow. However, the newly ploughed seabed can be rich in nutrients and stimulate diatom blooms which then attract grazers. Like in the anchor ice zone, these new scours provide space for poor competitors that could not occur without periodic disturbance. Fishes are then attracted, hunting for the small worms, crustaceans, and other early colonizers. Ice scour may also resuspend food particles. Thus, ice scour has positive influences as well. As long as the recurrence of ice scour is not so frequent that colonization cannot progress, an ice-scoured seabed can form a patchwork of colonists of various types, thus increasing overall biodiversity. Regional warming is resulting in thinner and less extensive sea ice, which would mean fewer pressure ridges scouring the inshore. On the other hand, glacier melt and breakup should produce more deep draft icebergs, such as the huge B-15 iceberg, part of which lodged off Ross Island in 2001 and affected the local penguin rookeries.

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See also **Algae; Benthic Communities in the Southern Ocean; Biodiversity, Marine; Echinoderms; Fish: Overview; Food Web, Marine; Icebergs; Marine Biology: History and Evolution; Pack Ice and Fast Ice; Phytoplankton; Sea Ice: Types and Formation; Zooplankton and Krill**

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ICE–ROCK INTERFACE

The nature of the ice–rock interface is poorly known in most parts of Antarctica. It is likely to be analogous to areas now exposed in North America and Europe that formerly underlay the Ice Age ice sheets, which contain distinctive suites of glacial landforms. The last Glacial Maximum ice sheet reached the continental shelf edge in many parts of Antarctica, and submarine areas exposed by glacial retreats show a subset of the glacial landform features seen elsewhere.

Observation of the ice–rock interface is restricted to field and remote-sensing studies of formerly glaciated areas; the drilling of boreholes (through kilometres or more of ice); and sounding using seismic (sound) or radar (electromagnetic) waves. Boreholes are either mechanically drilled or hot-water-drilled. Two mechanically drilled holes have reached the bed (at Byrd Station and Berkner Island), while numerous hot-water drillings have accessed the subglacial environment, particularly in the Siple Coast area. The latter have been well-instrumented, permitting measurements of water pressure and motion of ice over sediment beds as well as deformation within the sediment. The boreholes show a complex picture, with sediment frozen onto the base of the ice sometimes found, and the ice either slipping over the sediment or causing deformation within the sediment at some depth.

Seismic soundings discern whether the underlying bed is made of bedrock (solid rock created by nonglacial processes); stratified, generally nonglacial sediments; or unstratified or weakly stratified sediments which are presumably of glacial origin. Seismic soundings detect whether subglacial sediments are dilated (opened up), implying that the sediment is deforming or has been very recently deposited. Radar soundings inform about the geometry of the ice-bed contact and whether water is present, implying the occurrence of sliding and geological activity. Radar and seismic soundings suggest that material underlying the ice base is highly variable—sometimes bedrock, sometimes sediment, and sometimes ponded water.

The processes of erosion and deposition which shape the ice–rock interface are fundamentally governed by temperature. Towards their bases, ice sheets and glaciers warm as geothermal heat flow and frictional heating counteract the cooling effect of downward-moving ice. In many parts of Antarctica, the heating is sufficient to warm the ice to its melting point at the bed, and slip of ice over the bed can occur. Once this happens, rock and sediment at the bed can be fragmented and moved (erosion), or, where the transporting power of the glacier is decreasing, deposited. Material can be transported in a basal layer within the ice centimetres or metres thick, or in a layer of deforming sediment tens of millimetres to metres thick. In addition, flowing water at the glacier bed can cause erosion and deposition of sediment. The relative proportion of material transported by each process is poorly known, and probably varies strongly in space and in time.

Where ice is at the melting point it may melt or freeze, compensating warming and cooling trends in the ice. Water drains from melting areas and drains towards areas where there is freezing on of water. If there is insufficient water inflow, ice will freeze on to the bedrock or sediment. Sediment can be frozen to the base of the ice forming ice lenses and layered sediments.

The erosional effects of ice sheets are expressed throughout the world at a variety of scales (Benn and Evans 2003; Bennett and Glasser 1996)—large U-shaped valleys tens to hundreds of kilometres long and kilometres or even tens of kilometres wide; roche-moutonnées and whaleback forms (hillocks), tens to hundreds of metres wide; and small-scale polishing and friction marks. The clearest expression in Antarctica is through the large valleys cut through mountain ranges, which drain much of East Antarctica and parts of West Antarctica and the Antarctica Peninsula. A spectacular example is the valley containing the Byrd Glacier in the Transantarctic Mountains.

The primary depositional effect of ice sheets is the emplacement of subglacial sediments, or till. Till is generally a diamicton, that is, it contains grains of two distinct sizes, one clay-silt, the other stones centimetres in size. Subglacial till often shows that it has been deformed beneath the glacier, both through obvious tectonic features and from microscopic investigations of the fabric, which show characteristic patterns of grains related to deformation (Meer and others 2003). Abundant till is found on the Antarctic continental shelf. Till can be shaped into or draped over other forms, the most important of which in Antarctica are drumlins and megascale glacial lineations (Clark 1993). Drumlins are tens to hundred of metres high, and hundreds of metres to kilometres in plan form, typically in an ovoid form aligned with ice flow; megascale glacial lineations are subdued features, tens or hundreds of kilometres long and hundreds of metres to kilometres wide, aligned with glacial flow. Surface melt features ubiquitous in the Northern Hemisphere (e.g., eskers and, hummocky moraine) are not seen in Antarctica owing to the absence of such melt. Extensive zones of drumlinlike features have been discovered on the seabed in Antarctica, exposed by the retreat of the ice sheets, and also sounded through ice. Some spectacular arrays of megascale lineations have been found aligned along former ice-stream troughs (Canals et al. 2000).

Erosion of bedrock occurs by at least two distinct processes, plucking and abrasion. The latter occurs when tools (i.e., stones) gripped by moving ice or till are dragged over bedrock, resulting in striations (scratches) and polishing. Without abrading tools to perform scratching, erosion of the bedrock by clean ice would be very limited. The supply of tools is believed to be by plucking, which is the removal of blocks and stones of often prefractured rock by the ice. Observations of shattering show that this occurs mainly on the downstream (lee) side of obstacles of various sizes of a few tens of centimetres to tens of metres. The two main processes of erosion are believed to be responsible for the two particle-size families in diamict (till).

The origin of drumlins and related features remain as controversial as they were 2 centuries ago. Three principal mechanisms have been proposed: an instability in deforming till; dunes left by subglacial outburst floods; and interactions between ice flow and thermal regime. These mechanisms reflect different subglacial debris transport pathways. Observations of the rate of drumlin formation by seismic or radar sounding will therefore illuminate how sediment is being transported under glaciers.

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See also **Antarctic Ice Sheet: Definitions and Description; Earth System, Antarctica as Part of; Geological Evolution and Structure of Antarctica; Glacial Geology; Glaciers and Ice Streams; Ice Ages; Ice Sheet Mass Balance; Ice Sheet Modeling; Mega-Dunes; Neotectonics; Subglacial Lakes; Transantarctic Mountains, Geology of**

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ICE SHEET MASS BALANCE

Introduction

The Antarctic Ice Sheet changes shape and size over time as a result of a balancing act between snow being deposited (and subsequently compressed under its own weight to form ice) on the surface of the ice sheet, and the flow of the ice towards the coast where it discharges into the sea (either by melting or by iceberg calving). This ice sheet mass balance is positive if the amount of ice resulting from deposition on the ice sheet exceeds the amount flowing out (i.e., the ice sheet is growing), or negative if the amount of ice is less than that discharging from the area (i.e., the ice sheet is shrinking). Ice sheet mass balance can be examined at different elevation levels from the summit of drainage basins down to the terminus. It can also be considered over large areas (e.g., the entire Antarctic Ice Sheet), or over small areas (e.g., individual glacier accumulation basins). Because of the different bedrock topography and different climate regimes, the Antarctic Ice Sheet is often considered in two major sections, the East Antarctic Ice Sheet and the West Antarctic Ice Sheet, separated by the Transantarctic Mountains. Rignot and Thomas (2002) estimated the East Antarctic Ice Sheet mass balance to be positive; +22 $km^3\ yr^{-1}$ (433 $km^3\ yr^{-1}$ accumulation minus 411 $km^3\ yr^{-1}$ outflow). But they estimated the mass balance for the West Antarctic Ice Sheet to be negative; –48 $km^3\ yr^{-1}$ (381 $km^3\ yr^{-1}$ accumulation minus 429 $km^3\ yr^{-1}$ outflow).

Study of the Antarctic Ice Sheet mass balance is important and urgent because changes in the ice mass are closely linked to global sea level change. Variations in sea level over the past million years are highly correlated with changes in the global ice mass, and the response of the ice sheets to climate change in the future could raise global sea level. For the short term, however, the Intergovernmental Panel on Climate Change (IPCC) estimated that the Antarctic contribution to twentieth-century sea level rise (Church and Gregory 2001) was a lowering of between 0.2 and 0.0 mm yr^{-1}. This estimated lowering results because atmospheric warming may result in an increase in snow accumulation over the cold ice sheet (e.g., Polar Research Board 1985). In this scenario in the longer term (hundreds to thousands of years), however, this increased accumulation would result in an increase in sea levels as the increased mass of ice moved to the coast and dissipated into the ocean. On the other hand Kapsner et al. (1995) and Cuffey and Clow (1997) cite cases in which warming does not lead to higher accumulation. It is expected also that the influence on sea level of higher accumulation may be counterbalanced by increased basal melting from the floating ice shelves. Basal melting is estimated to account for up to one third of the loss from the ice shelves within which much of the Antarctic Ice Sheet terminates (Jacobs et al. 1996). While ice shelf basal melting is important for considerations of the Antarctic Ice Sheet mass balance, it has no direct effect on sea level since the ice is already floating. However the significance of the role of the oceans through melt could be important in a warming climate. If melt rates increase due to ocean warming, this could have an indirect but significant effect on ice discharge, leading to sea-level rise.

Two different but complementary techniques are used to measure ice sheet mass balance. The first is the component (or flux) technique in which the input and output fluxes are individually measured or estimated. This technique is particularly important when applied to individual drainage systems within the ice sheet, and can be used to isolate the causes of mass balance change. The second is by direct measurement of mass changes without separately determining the input and output fluxes.

The Component Technique

The Input Component

The input component to ice sheet mass balance is the net accumulation of snow at the surface. Additional minor effects include atmospheric frost deposition and wind export of drift across the coast. Accumulation rates are most commonly estimated by measuring the thickness of annual layers in ice cores, but because the number and spatial coverage of ice cores across the ice sheet is poor (even though several new ice cores have been drilled over the past decade), current estimates of mass input have large errors. For the future, there is some promise that space-borne techniques (Bolzan and Jezek 1999; Winebrenner et al. 2001) will soon provide an improved picture of the accumulation distribution across the ice sheet, and new techniques such as ground penetrating radar (GPR) profiling of firn stratigraphy, precise global positioning system (GPS) positioning, and direct measurement of ice thickness change (measuring the position of firn anchors) (Hamilton et al. 1998) will improve the coverage and accuracy of accumulation data. The International Trans-Antarctic Scientific Expedition (ITASE) (Mayewski and Goodwin 1997) provides an ideal opportunity for these measurements.

Once the snow has deposited on the ice sheet surface, it is subject to redistribution by the wind, and sublimation, densification, and metamorphism. These processes need to be well understood before the ice sheet mass balance input can be accurately assessed. At the same time, climate models can be used to estimate the precipitation over the ice sheet, but these must be physically based and tested against the measurements.

The Output Components (Ice Dynamics, Fluxes, Melt/Freeze, Calving)

The output term for the component technique is the ice flux across the downstream margin of the area under consideration (e.g., if considering the entire

Antarctic Ice Sheet, the coast). The flux is the product of the distance across the downstream margin, the mean ice thickness across the downstream margin, and the mean ice velocity through the margin. Thus we need detailed measurements of ice thickness and ice velocity. To understand the mass balance of the entire Antarctic Ice Sheet, we require these measurements in detail across the entire ice sheet. Of particular importance is the mass balance of the grounded ice, so we need to know the location of the grounding zone (the zone in which the ice begins to float, becoming separated from the land). This is not easy, given that it is covered by the ice (several hundreds of metres thick). New satellite remote sensing data have led to major advances in our current knowledge of the location of the grounding zone, especially in the important regions of fast glacier outflow (e.g., Rignot 2002), coastal ice flux, and inferred ice shelf bottom melting. From these data, we have learned that major changes are taking place at several specific locations in the Antarctic (e.g., Pine Island and Thwaites Glacier basins) on much shorter timescales than previously thought. If we assume the ice sheet is in balance (i.e., the snow accumulation is balanced by the flux) then, with knowledge of each of the other terms, we can calculate what the ice velocity distribution would be. This velocity is called the "balance velocity" and comparison of its values with actual measured values provides a good estimate of whether the ice sheet is in balance, growing, or shrinking. There have been several major advances in recent years towards more accurate estimation of ice sheet mass output. These have included continental-scale mapping of balance velocity and ice surface and bedrock topography (Bamber et al. 2000; Budd and Warner 1996; Lythe and Vaughan 2001) and observations and estimates of ice velocity on large outlet glaciers and Siple Coast ice streams (Rignot 2002).

The Integrated Technique

For the integrated technique, changes in the volume and mass of the ice sheets can be determined by satellite measurements of changes in ice-sheet surface elevation. Corrections are required, however, for the vertical motion of the underlying bed (due to height changes in the bed rock caused by compression due to the load of the ice above) and for variations in near-surface firn density (due to temperature, the accumulation itself). Changes in the bedrock are estimated from coupled models of the ice and lithosphere dynamics (Le Meur and Huybrechts 1996). In addition, measurements of changes in the Earth's gravity field, from observed perturbations to satellite orbits, can be related to changes in the mass of ice (Bentley and Wahr 1998).

The best currently available data of surface elevation change for the Antarctic Ice Sheet comes from satellite radar altimetry (most notably so far from the Earth Resources Satellites ERS-1 and ERS-2 for the period 1991–2001). New radar (ENVISAT and CryoSat) and laser altimeter (GLAS/ICESat) satellite missions will extend these data for another decade. ICESat and CryoSat will also provide information on surface elevation change with time in regions where the ice surface is changing the most (the fast-flowing outlet glaciers and ice margins). Recent results (Shepherd et al. 2002; Zwally et al. 2002) from analysis of ERS-1 and ERS-2 altimeter heights have provided the most accurate measurements so far of ice sheet mass balance (e.g., showing that the portion of the grounded ice sheet upstream of the Pine Island and Thwaites Glaciers has thinned by up to 30 cm yr^{-1} over the past decade).

Conclusion

One of the longest standing and most important problems in polar science is also the most challenging to understand. Despite several international programs over the past 50 years to examine the mass balance of the Antarctic Ice Sheet, the relationship between the large ice sheets and sea level change is still not completely understood, and we are still not certain whether the ice sheet is growing, shrinking or in balance. A recent assessment of Antarctic Ice Sheet mass balance studies (ISMASS Committee 2004) stated that "the 20th century Antarctic mass imbalance seems near to zero or slightly negative. The newly recognised importance of ice shelf melting now emphasises mechanisms that may offset the 21st century expected growth due to global warming."

T. H. Jacka

See also **Antarctic Ice Sheet: Definitions and Description; Climate Modelling; CryoSat; Firn Compaction; Ice Core Analysis and Dating Techniques; Ice Shelves; Icebergs; ICESat; Remote Sensing; Snow Post-Depositional Processes; Surface Mass Balance; Thwaites and Pine Island Glacier Basins; Wind**

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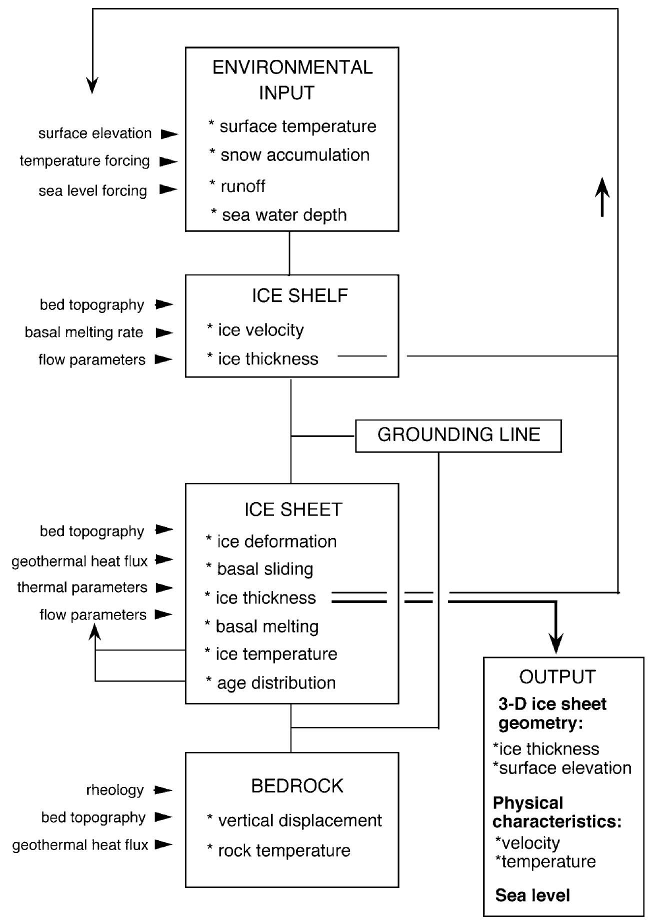
ICE SHEET MODELING

Ice sheet modeling underpins much of our understanding of the Antarctic Ice Sheet. A primary motivation for developing mathematical models of ice flow is to gain better insight of the key processes controlling ice-sheet behaviour and to predict the ice sheet's response to external forcing. Modeling necessarily implies a simplified description of reality, however analytical methods can only be used for the most simple problems. Therefore, ice-dynamic models use numerical methods to solve continuous equations on a numerical grid with the aid of a computer. Ice-flow models are commonly based on fundamental physical laws and assumptions thought to describe glacier flow.

Models can be separated into two categories, namely diagnostic and prognostic models. A diagnostic model describes a certain process while a prognostic model predicts how a quantity or process evolves with time. Diagnostic ice-sheet models often isolate a small part of the ice sheet in great detail or consider the physics of a specific process in a schematic way. They are useful to highlight the importance of certain mechanisms and provide insight in key processes governing ice flow. Prognostic models mostly predict the evolution of ice thickness and thus glacier geometry over time. Such models often attempt to be comprehensive in the number of processes taken into account, however sometimes at the expense of a rigorous consideration of the full details of a particular component.

A further distinction can be made on how models embody horizontal space: either they study the dynamics of selected one-dimensional flowlines within the ice sheet or they study the ice sheet in the full two-dimensional horizontal plane. The former type is often referred to as flowline or flowband model and the latter as planform model. Planform models often average processes over the vertical extent, in which case these models are referred to as two-dimensional planform or vertically integrated models. Otherwise they incorporate vertical processes explicitly. Examples of such vertical processes are ice temperature, stress, and velocity components, as well as ice crystal fabric and water content. Such models are called three-dimensional thermomechanical models and are at the top end of the class of ice-sheet models. They are able to describe the time-dependent flow and shape of real ice sheets, and are akin to general circulation models developed in other branches of climate science. Their development closely follows technical process in such fields as computer power, ice-core and sediment drilling, remote sensing, and geophysical dating techniques, which are both providing the required calculating means and the necessary data to feed and validate such models.



Structure of a comprehensive three-dimensional ice-sheet model applied to the Antarctic ice sheet. The inputs are given at the left-hand side. Prescribed environmental variables drive the model, which has ice shelves, grounded ice, and bed adjustment as major components. The position of the grounding line is not prescribed, but internally generated. Ice thickness feeds back on surface elevation, an important parameter for the calculation of the mass balance. The model essentially outputs the time-dependent ice-sheet geometry and the coupled temperature and velocity fields. (From Huybrechts 2004.)

Historically, planform time-dependent modeling of ice sheets largely stems from early work by Mahaffy (1976) and Jenssen (1977), extending on the pioneering "Derived Physical Characteristics of the Antarctic Ice Sheet" of W. F. Budd and colleagues at the Australian National Antarctic Research Expeditions published in 1971. These landmark studies introduced many concepts and techniques that are still used in glaciology today. The most important concept made use of the fact that the horizontal extent of an ice sheet is large compared with its thickness. In what became known as the shallow-ice approximation (Hutter 1983), longitudinal derivatives of stress, velocity, and temperature are assumed small compared to vertical derivatives. This greatly simplifies the numerical solution. Although the assumption is only fully satisfied over inland portions of continentally based ice, it has shown general applicability in large-scale ice-sheet modeling as long as surface slopes are evaluated over horizontal distances at least an order of magnitude greater than ice thickness.

The core of an ice-sheet model calculates how ice flows downhill in response to stresses set up by gravity. This ice flow results from internal deformation and from ice sliding over its bed where the basal temperature has reached the melting temperature and a lubricating water-saturated layer has formed. Whereas basal sliding depends to a large extent on the properties of the bed under the ice, internal deformation is the inherent manifestation of individual ice crystals subjected to stress. This deformation is reasonably well understood on the macro scale and can be reliably modelled taking into account Glen's flow law. That is an empirical relation derived from laboratory tests, which is most commonly used in ice flow modeling. It considers ice as a nonlinear viscoelastic fluid, relating strain rates to stresses raised mostly to the third power. The rate of deformation for a given stress also depends on the temperature of the ice and the fabric of the ice. The warmer the ice, the easier it deforms. For the temperature range encountered in the Antarctic Ice Sheet, three orders of magnitude are involved. In the flow law, this temperature effect is usually incorporated by adopting a temperature-dependent rate factor. If the ice temperature is calculated simultaneously with the velocity field, the flow is called thermomechanically coupled. In some instances, the ice has developed a strong fabric, with the majority of crystal axes aligned in one preferred direction, making the ice ‘‘soft’’ with respect to some stress and ‘‘hard’’ with respect to other stresses. Such fabric development may influence the strain for a given stress by an additional factor 3 to 10.

Because glacier flow is sufficiently slow that accelerations can be neglected, Newton’s second law of motion reduces to an equilibrium of forces. The action force making ice flow in the direction of decreasing surface elevation is the driving stress. This action is opposed by resistive forces acting at the boundaries of the ice mass. These boundaries include the glacier bed (basal drag), the lateral margins (lateral drag), and the up- and down-glacial ends (gradients in longitudinal stress). In interior portions of ice sheets, the force balance is essentially between the driving stress and basal drag as predicted by the shallow-ice approximation. In floating ice shelves, there is negligible basal friction and the driving stress is balanced by gradients in longitudinal stresses and by lateral drag. This makes the velocity calculation nonlocal as opposed to inland ice flow. In ice shelves, driving stress is balanced more broadly, so that modelling the behaviour at any point requires knowledge of all of the surrounding stresses affecting the ice mass. Lateral drag and longitudinal stress gradients also play an important role in the fast outlet glaciers and ice streams that are responsible for the bulk of the ice discharge towards the margin. As such they represent a transitional region between inland-ice and ice-shelf dynamics. Because of the low driving stresses in the downstream portions of such ice streams, much, if not all, of the differential flow between the ice surface and the bedrock is caused by either basal sliding or by deformation of a subglacial mud (till) layer. Fast-glacier conditions at the base are, however, poorly understood. Processes related to bed roughness, till rheology, and basal water pressure are all thought to be important elements, but a realistic basal boundary condition for use in numerical models has not yet been developed.

Based on these principles, the advent of bigger and faster computers has allowed elaborate numerical models of the Antarctic Ice Sheet to be constructed. At the heart of such a model is the simultaneous solution of two evolutionary equations for ice thickness and temperature, together with diagnostic representations of the ice velocity components. These express fundamental conservation laws for momentum, mass, and heat, supplemented with Glen’s flow law for polycrystalline ice deformation. The model solves the thermomechanically coupled equations for ice flow in three subdomains, namely the grounded ice sheet, the floating ice shelf, and a stress transition zone in between at the grounding line. The flow within the three subdomains is coupled through the continuity equation for ice thickness, from which the temporal evolution of ice sheet elevation and ice sheet extent can be calculated by applying a flotation criterion. The latter treatment allows for migration of the grounding line, separating the land-based ice from the surrounding ice shelf, in response to changes in climatic boundary conditions. The various subdomains reflect the two major traditions of ice-deformation modeling, evident in the very different physical conditions in ice shelves versus inland ice. An important difficulty in whole ice-sheet models lies with the coupling of grounded ice flow with floating ice flow and with modeling flow in complex regions such as ice streams, where the simplifying assumption that one shear stress largely dominates inland flow and one stretching stress largely dominates shelfy flow breaks down. Progress is being made in ice-flow models to combine the two traditions of ice-flow modeling in a more comprehensive fashion (e.g., Pattyn 2003; Payne et al. 2004). However, a full calculation of the complete stress distribution for whole-ice-sheet integrations over longer time periods is numerically not yet feasible.

Whole-ice-sheet modeling of the Antarctic Ice Sheet further involves simulation of surface mass fluxes (snow fall, wind drift, sublimation, melting followed by runoff or refreezing), sinking or rising of the underlying bedrock in response to changing ice load, heat transfer under the ice and into the bedrock affecting melting/frozen regions and the deformation rate of ice, interactions of ice shelves with the ocean, and more. Interaction with the atmosphere and the ocean in large-scale Antarctic Ice Sheet models is carried out by prescribing the climatic input, consisting of the surface mass balance (accumulation minus ablation, if any), the surface temperature, and the basal melting rate below the ice shelves. Changes in these fields are often heavily parametrized in terms of air or ocean temperature but can also be derived from calculations with atmosphere and ocean models. Models of this type are usually forced by time series of regional temperature changes (available from ice-core studies) and by the eustatic component of sea-level change, relative to present values.

Three-dimensional ice sheet models are typically implemented using finite-difference techniques on a regular grid of nodes in the two horizontal dimensions, and using a stretched coordinate system in the vertical. Horizontal grid resolutions are mostly in the range of 10 to 50 km with between 20 and 100 layers in the vertical, concentrated towards the base where the bulk of the deformation takes place. In finite-difference models, gradients of continuous functions are obtained by dividing the values of the parameter at grid points by the distance between the grid points. Finite element implementations also exist but these are often restricted to a smaller domain. An advantage of the finite element method is that the element size can be reduced in areas of high gradients and increased in areas of low gradients. Furthermore, element shapes can be adjusted to conform to boundaries that would otherwise be awkward to model with rectangular elements. However, changing spatial patterns over time and varying ice-sheet domains have proven to be a challenge to the popularity of finite-element methods in glaciological modeling. Recent Antarctic model studies have benefited from much improved compilations of crucial input data such as bed elevation, surface elevation, and ice thickness that became available on high-resolution grids from the BEDMAP project (Lythe et al. 2001).

Three-dimensional models of the Antarctic Ice Sheet have been used to examine mechanisms and thresholds of ice-sheet inception during the Tertiary (DeConto and Pollard 2003), the expansion and contraction of the Antarctic Ice Sheet during the glacial-interglacial cycles (Huybrechts 2002), and the likely effects of greenhouse-induced polar warming (Huybrechts et al. 2004). In this context, the key interactions being investigated are between the effects of a change in climate on the accumulation and ablation fields and the ice sheet's response in terms of changed geometry and flow, including the ice sheet's contribution to the worldwide sea level stand. Related work considers the Antarctic Ice Sheets as a boundary condition for other components of the Earth's geophysical system, providing changes in surface loading for isostasy and gravity models, or providing changes in freshwater fluxes for ocean models. Thermomechanical ice-sheet models are also being used to investigate the potential for internally generated flow instabilites, especially concerning the West Antarctic Ice Sheet, or explain recently detected accelerations of outlet glaciers taking into account higher-order stress calculations (Payne et al. 2004). The general appreciation is that current models available to the community perform best for the largely continental-based East Antarctic Ice Sheet; however, many challenges pertain to the modelling of the marine-based West Antarctic Ice Sheet.

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See also **Antarctic Ice Sheet: Definitions and Description; Climate; Climate Change; Earth System, Antarctica as Part of; Glaciers and Ice Streams; Ice Ages; Ice–Rock Interface; Ice Sheet Mass Balance; Ice Shelves; Icebergs**

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ICE SHELVES

General Characteristics

Ice shelves are the floating parts of an ice sheet. They form at the margins where the ice sheet becomes thin enough to float free of a bed that lies below sea level, allowing seawater to circulate beneath the ice. Ice-shelf-like features also form in the interior of ice sheets where the ice floats on subglacial lakes. Dynamically, ice shelves are distinct from other parts of the ice sheet in that they rest on a frictionless substrate, so that ice motion is controlled only by the degree of lateral confinement.

Antarctica contains most of the ice shelves that currently exist on Earth. They range in thickness from less than 100 m to over 2000 m and individually cover areas of up to 0.5 million km^2. Although their combined area is only 13% of that of the grounded ice sheet, around 80% of the grounded ice drains into the ice shelves before being lost to the oceans. Ice shelves thus play a critical role in the overall ice budget of Antarctica.

Elsewhere, especially in Greenland, glaciers that terminate at the coast often have short tongues of floating ice. Although technically ice shelves, they are normally too small to be attributed a name distinct from that of the parent glacier. The larger ice shelves of Antarctica are different in that they are fed by multiple glaciers, the outflows from which coalesce to form a distinct glaciological feature.

Ice floating on water tends to spread horizontally and thin, in a manner analogous to that of a drop of oil, only much slower owing to the much higher viscosity of ice. This process gives rise to the typical ice shelf profile with thick ice at the inland margin becoming progressively thinner with distance downstream (i.e., with time afloat). The horizontal spread of the ice also means that the velocity of the ice increases with distance downstream with speeds reaching kilometres per year at the ice fronts. The forces that drive the spreading are proportional to ice thickness, so the thicker the ice the more rapidly it tends to thin. Over time this process evens out small-scale thickness variations leading to a progressively smoother upper surface. This lack of surface topography is a characteristic feature of ice shelves.

Most ice shelves are confined within embayments, or contain regions where the ice runs aground on the seabed. Horizontal spreading of the ice is then restricted in one or more directions and the rate of thinning is reduced. Such confinement is thought to be critical to the stability of the larger ice shelves. Reduction in the amount of confinement, caused for example by thinning of the ice reducing the area of contact with the seabed, could lead to breakup of the ice shelves.

Ice shelves are fed by the flow of ice from grounded parts of the ice sheet and by snowfall on the upper surface. In some places accumulation of mass also occurs at the lower surface, through the freezing on of seawater. Mass loss occurs predominantly by the production of icebergs, a process known as calving, and by the melting of ice from the underside. Calving from ice shelves tends to produce massive tabular icebergs, the largest of which can exceed 10,000 km^2 in area. More rarely, some mass loss occurs by surface melting or sublimation.

As ice shelves are already afloat, the direct contribution to global sea level rise that would be associated with their decay or disintegration is small. It is nonzero because the freshening caused by melting of the ice would lead to a small expansion of the ocean, giving a sea level rise of around 3 cm if all the water in the ice shelves were distributed globally within a layer of seawater 300 m thick. However, a confined ice shelf provides a resistive force that is felt by the ice streams that discharge grounded ice into it. Removal of an ice shelf can thus cause accelerated flow across the grounding line, at least temporarily while the ice streams adjust to the new conditions. The likely magnitude and duration of such an adjustment is still the subject of debate. Being in contact with both the atmosphere above and the ocean below, ice shelves are seen as sensitive indicators of climate change in Antarctica.

At the time of the last glacial maximum (LGM), around 18,000 years ago, the Antarctic Ice Sheet expanded to cover most of the continental shelf. The current configuration of ice shelves around Antarctica is the product of thinning and retreat of the ice sheet as the Earth's climate entered the current interglacial stage and temperatures and sea level rose worldwide. It is an open question as to whether the ice sheet and surrounding shelves have completed their adjustment to this change in climate.

Ice Shelf Research

The first sighting of one of Antarctica's vast ice shelves was made in 1841, when James Clark Ross discovered the ice shelf that now bears his name. He made water depth soundings along part of the ice front, and deduced that the ice must be floating. The generally flat and crevasse-free surface of the ice shelves meant that they became the avenues by which many of the exploratory expeditions of the early twentieth century accessed the interior of the ice sheet. The ice shelves were hence the subjects of much of the early glaciological work in Antarctica, which started during the exploratory era and culminated in the International Geophysical Year of 1957–1958. Determining the thickness of the ice and underlying water layer were the major goals. Measurements of ice shelf motion were hampered by the complete lack of fixed reference points away from the ice shelf margins.

The 1950s were a period of major advance in the understanding of ice flow. Because of their relatively simple dynamics, with frictionless upper and lower surfaces, ice shelves became test-beds for the new theories of ice deformation. Studies undertaken in Antarctica during the 1960s and early 1970s demonstrated that the behaviour of large ice masses was consistent with an ice flow law that had been developed from laboratory scale observations.

In the late 1960s the advent of satellite navigation techniques revolutionised the study of Antarctic ice shelves. The motion of points in the interior of even the largest ice shelves could now be measured with high accuracy. A major survey of the Ross Ice Shelf was undertaken during the 1970s, with a variety of measurements being made at 200 sites evenly distributed over the ice shelf. The new data on ice motion and the rapid growth of computer power stimulated the development of numerical models of ice shelf flow that still underpin our understanding of ice shelf behaviour.

Concurrent with the 1970s survey, a hole was drilled through the Ross Ice Shelf to access the ocean beneath at a point 500 km in from the ice front. These were the first observations made deep within the cavity beneath a large ice shelf and indicated that an active circulation must flush seawater in and out. Early theories of the ocean circulation and of the resultant melting and freezing at the ice shelf base were advanced during the late 1970s and early 1980s. Most of the work that has been undertaken on Antarctic ice shelves during the 1990s and into the twenty-first century has been aimed at improving our knowledge of these processes and their role in determining both the mass balance of the ice shelves and the properties of the underlying ocean. The drilling of access holes, particularly through the Filchner-Ronne Ice Shelf and more recently the Amery Ice Shelf, ship-based surveys along the ice fronts and the application of increasingly sophisticated computer models of the ocean beneath the ice shelves have been at the heart of recent advances in understanding.

Developments in satellite remote sensing technology have gradually opened up new techniques for ice shelf research. Early imagery was used to track the motion of ice fronts and large features visible on the ice shelves. The initial slow retreat and eventual rapid disintegration of Wordie and parts of Larsen Ice Shelf were observed in this way. Increasingly accurate radar altimeters, used to measure the surface elevation of the ice, have shown that many ice shelves on the Antarctic Peninsula and in the Amundsen Sea are thinning at rates of the order of 1 m yr^{-1}. Satellites carrying advanced radar can detect ice motion, and accelerations in the flow of ice shelves in the Amundsen Sea have been observed. Understanding the causes and consequences of these changes is one of the major goals of current ice shelf research. Although it is believed that atmospheric warming has been responsible for changes in the Antarctic Peninsula, the causes of the changes in the Amundsen Sea are unknown. They could reflect continuing retreat of the ice sheet following the LGM, or could be driven by changes in the ocean leading to increased basal melting.

Interaction with the Ocean

Their strong interaction with the seawater beneath them is a defining feature of ice shelves. The fundamental cause of this interaction is the pressure dependence of the freezing point of seawater. The deeper one goes in the ocean, the higher the pressure and the lower the freezing point of the water. Seawater that is cooled through contact with the atmosphere cannot be made colder than about –1.9°C. At this temperature ice begins to form. However, the temperature at which the phase change occurs falls by about 0.75°C for every 1000 m of water depth. Seawater that is cooled through contact with the base of an ice shelf can therefore attain a temperature lower than the surface freezing point. Water that has such a property is referred to as ice shelf water (ISW).

When seawater that is warmer than its depth-dependent freezing point comes into contact with the base of an ice shelf, it gives up some of its heat to melt ice. This is true even when the temperature of the salty water is lower than the melting point of the pure ice making up the ice shelf. In this case the process is technically one of dissolution rather than melting. Ice dissolution is the mechanism by which salt sprinkled on roads can clear them of ice even when the air temperature remains well below zero. Melting (or dissolving) the ice shelf freshens the seawater, lowering its density.

Water flowing into the cavity beneath an ice shelf cannot be colder than its surface freezing point, unless it has been in prior contact with another ice shelf. The water is therefore warmer than its freezing point at depth. When it contacts the ice shelf base the ice melts. The fresher, less dense ISW rises towards the surface, constrained by the sloping ice shelf base. As the ISW rises melting continues as long as the water temperature remains above the freezing point. However, as the water ascends, the falling pressure means that its freezing point rises. Eventually the ISW temperature drops below the rising freezing point and melting gives way to freezing at the ice shelf base. The ice that forms is virtually pure and the salt left behind in the ISW increases its density. This process continues until the ISW is no longer lighter than the surrounding water and thus ceases its rise along the ice shelf base. The overall result is an overturning circulation that melts ice from the deepest parts of the ice shelf base and freezes ice onto the shallower parts. The whole system is sometimes referred to as an "ice pump." Where the ice shelves are very thick at their inland margins, melting and freezing rates of metres of ice per year result.

Around most of the Antarctic coastline the winters are sufficiently cold that all the waters close to the ice shelves are cooled to the surface freezing point. Thus, further cooling beneath an ice shelf inevitably produces ISW, as described previously. However, along the coasts of the Amundsen and Bellingshausen seas, subsurface water temperatures can exceed 1°C throughout the year. Melt rates in excess of 10 m yr^{-1} can result, and there is no freezing beneath the ice shelves, because the water is never cooled sufficiently to form ISW. The warm water is a derivative of Circumpolar Deep Water (CDW), and understanding the reasons for its presence on the continental shelf is a critical step in defining the cause of the ice shelf thinning in the Amundsen Sea. If CDW were to gain access to the continental shelves in other regions we would see major thinning of Antarctica's ice shelves. Reduction in the amount of ISW produced would also have consequences for the global ocean circulation, since ISW is one ingredient in the densest form of Antarctic Bottom Water (AABW). AABW is found at the bottom of the ocean throughout most of the world, and its formation around Antarctica is one component of the global overturning circulation that regulates the Earth's climate.

ADRIAN JENKINS

See also **Antarctic: Definitions and Boundaries; Antarctic Ice Sheet: Definitions and Description; Antarctic Peninsula; Antarctic Peninsula, Glaciology of; British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); Coastal Ocean Currents; CryoSat; Eddies in the Southern Ocean; Filchner-Ronne Ice Shelf; Firn Compaction; Glaciers and Ice Streams; Ice Sheet Mass Balance; Ice Sheet Modeling; Icebergs; ICESat; International Geophysical Year; Lake Ellsworth; Lake Vostok; Lambert Glacier/Amery Ice Shelf; Larsen Ice Shelf; RADARSAT Antarctic Mapping Project; Remote Sensing; Ross Ice Shelf; Southern Ocean; Southern Ocean: Climate Change and Variability; Subglacial Lakes**

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ICEBERGS

An iceberg is a floating mass of freshwater ice that has broken from the seaward end of a glacier or ice shelf. Icebergs are found in the oceans surrounding Antarctica, in the seas of the Arctic and sub-Arctic, and in fjords and lakes fed by glaciers. In the Antarctic, typical newly calved icebergs are tabular, with diameters of order kilometres, thicknesses of 200–300 metres and freeboards of 30–50 metres, giving a mass of order a billion tons.

Origin

Most Antarctic icebergs calve from floating ice shelves, which occupy one-third of the Antarctic coastline. The shelves are fed at their landward ends by the Antarctic Ice Sheet, and their seaward fronts are afloat. Under the pressure of ice squeezing outwards from the centre of the continent, ice shelves move seaward at 0.3–2.6 kilometres per year. Their fronts are exposed to stresses from currents, tides, ocean swell in summer, and the pressure of drifting pack ice in winter. Eventually a fracture occurs, often along an existing line of weakness such as a crevasse, to produce a freely floating iceberg. Some apparently minor ice shelves are prolific generators of icebergs because of their rapid velocity (e.g., the small Amery Ice Shelf drains one-eighth of the Antarctic Ice Sheet and produces 31 cubic kilometres of iceberg volume annually).

Direct observations of iceberg calving are rare. The calving of a large iceberg has been observed immediately after the ice front had been hit by another iceberg, implying that the collision caused the calving. A special mechanism occurs in the case of glacier tongues, long narrow floating ice tongues which are the output of especially fast-flowing glaciers. Here calving can be caused by long ocean waves which cause the tongue to oscillate until it fails in flexure. The recent mass breakout of icebergs from Antarctic Peninsula ice shelves, ascribed to global warming, is thought to occur because surface meltwater in summer fills crevasses at the top surface and produces a tensile stress at the crevasse base.

Some Antarctic icebergs calve from glaciers which originate in coastal mountains, such as those parts of the Transantarctic Mountains which form the Antarctic Peninsula or face the Ross Sea coast. Because such glaciers are narrow, fast-flowing, and riven with crevasses, the icebergs are usually smaller than bergs of ice shelf origin and are more randomly shaped.

Structure

A new Antarctic tabular iceberg has the same structure and physical properties as its parent ice shelf. This implies that the freeboard of the iceberg, the above-water part, is not actually ice at all but rather compressed snow. The ice shelf has the same layered structure as the continental ice sheet from which it was squeezed out, with recently fallen snow on top, and older annual layers beneath. Each layer is compressed by the snow above it, so that density increases with depth. A typical density profile through an ice shelf or iceberg shows that at the top, where the density might be only 400 kg per cubic metre (pure ice has a density of 920), there is free passage for air or water through the spaces between the crystal grains. When the density reaches 800 kg per cubic metre, deeper in the berg, the air channels close off and turn into isolated bubbles. At this point the material becomes truly "ice," as opposed to the material above, which is called firn. Ice begins some 40–60 m below the surface of the iceberg, which corresponds approximately to the waterline and to about 150–200 years of snow deposition. Further increases in density towards the iceberg bottom are associated with the compression of the air bubbles; pressures within bubbles in glacial ice have been measured at 10–15 atmospheres, with the bubbles tending to be spherical or ellipsoidal, of diameter 0.33–0.49 mm, and with mean diameter decreasing with increasing depth.

The upper part of a recently calved berg is significantly warmer than its parent ice shelf. As soon as the berg drifts into more temperate regions, especially when it drifts free of the surrounding pack ice cover, it begins melting at its upper surface. The meltwater percolates through the permeable uppermost 40–60 m, refreezing at depth and giving up its latent heat. By this means the above-water part of a tabular iceberg is brought relatively quickly to temperatures close to the melting point. With its warm temperature and low density, this part of the berg has little strength and is easily eroded away. The main mechanical strength of the iceberg resides in the "cold core" below sea level, where very low temperatures of –15°C to –20°C remain, and where latent heat transfer through percolation and refreezing is impossible.

Sizes and Shapes

Antarctic tabular icebergs can be extremely large. One measuring 180 km square with a freeboard of 30–40 m was seen off Clarence Island by the whalecatcher *Odd I* in 1927; though it was the largest reliably observed at the time, it has been eclipsed by others, including the 2000 calving of B-15, accurately observed via satellite. Recently many giant icebergs have been seen in the Antarctic, and ascribed to climate change. It is true that the Antarctic Peninsula has warmed significantly in recent years (by 2.5°C since the 1950s), and that, apparently as a consequence, three of its ice shelves, the Wordie and Wilkins on the west side and the Larsen on the east, have been disintegrating, emitting large numbers of icebergs. Each retreat of the Larsen Ice Shelf since 2000 involved the release of a vast area of shelf ice in the form of giant icebergs. A 2002 breakout involved 3250 km^2 of shelf lost in 35 days.

However, the remainder of the Antarctic is not warming at present, and emissions of large icebergs are sporadic events that are probably no more frequent than in the past but are now more easily detected by satellite. For example, a giant berg that approached the coast of Argentina in November 1999 was iceberg B-10A (labelling system of Joint Ice Center, Suitland, Maryland), of dimensions 38 × 77 km and a reported freeboard of 90 m. It calved from the Thwaites Glacier in the Amundsen Sea and spent long periods aground; in 1995 it broke into two.

A decade earlier, two giant iceberg events occurred on opposite sides of the Antarctic. Iceberg B-9 calved from the Ross Ice Shelf in 1987 between the Bay of Whales and King Edward VII Peninsula, destroying the Bay of Whales (used by Amundsen as a base in 1910–1912) as a feature of the Ross Ice Shelf front. At calving it was 154 km long (the second longest iceberg ever) and 35 km wide with an area of 4750 km^2. The ice shelf front was advancing at 0.84 km per year. About twenty-four other large icebergs were produced in this event. The average thickness of the area of shelf that calved was 230 m, giving a volume of 1100 km^3 for B-9, equivalent to an average year's calving from the entire Antarctic coast, and equal to about 0.6% of the volume of the Ross Ice Shelf. The berg remained in the eastern Ross Sea region for 2 years, moving mainly with the depth-integrated current. In the Weddell Sea, two independent calving events occurred in 1986. On the Larsen Ice Shelf a 95 $\times$ 95 km section broke away in January–March 1986 followed by a 55 $\times$ 50 km section in July. On the Filchner Ice Shelf a 90 $\times$ 210 km area broke out in June, carrying with it the Russian Druzhnaya research station. The Filchner icebergs remained in place for some time after calving, but the Larsen icebergs quickly emerged into the Southern Ocean east of Clarence Island.

In the ice-free Southern Ocean, surveys of iceberg diameters show that most bergs are of diameter 300–500 m, with few exceeding 1 km. Stability calculations lead to the conclusion that wave-induced flexure breaks down most larger tabular bergs to this range of sizes, leaving a few exceptionally large bergs intact.

Antarctic bergs are usually tabular at the time of calving (although domed or concave, depending on the local shape of the ice shelf), but evolve via further calving to tilted shapes, or by erosion of the above-water part to a variety of more random shapes.

Erosion and Melting

After an Antarctic tabular iceberg emerges into the open ocean, it has little remaining strength above the waterline, which becomes subject to wave action. The high level of turbulence along the waterline increases heat transport into the ice and preferentially melts out a wave cut that can penetrate for several metres into the berg, such that the snow and firn above it collapse. At the same time the turbulence level is enhanced around existing irregularities in the berg, such as cracks and crevasses. Waves eat their way into these, and turn cracks into caves whose unsupported roofs may also collapse. Through these processes a berg in the open sea leaves a trail of broken-off fragments, called growlers if they are small and bergy bits if they are larger (according to World Meteorological Organization definitions, a growler is the size of a grand piano while a bergy bit is the size of a small house). Eventually through these inroads the iceberg may evolve into a drydock or pinnacled berg, composed of apparently independent elements that are in fact joined together below the waterline. Such a berg may look like a prehistoric stone circle, with shallow water in the centre.

Apart from losses due to erosion, pure melt also occurs from the sidewalls and bottom. The melt rate depends on the salinity and temperature profiles of the water column as well as the relative velocity between the berg and the near-surface water. Most estimates of melt rate are based on tank measurements of the melt of vertical ice walls. A variety of effects are seen, because of the cooling and dilution that occur when ice melts into salt water. The molecular diffusivity of salt is much less than that of heat, so diluted water remains near the wall while the cooling diffuses further from the ice. In unstratified water this causes a bidirectional flow, with a horizontal flow inwards towards the wall, changing into an upwelling flow directly against the wall and, at greater depths, a downward flow some distance from the wall. With a salinity gradient, however, a series of discrete steps can be produced, each of constant temperature and salinity, but with temperature decreasing and salinity increasing with depth. The slight inclination of the step boundaries to the horizontal results in a net upwelling as well as a flow of meltwater away from the berg. In the field, this "staircase structure" has been observed in measurements made close to the ice front of the Erebus Glacier Tongue, but in open water turbulence tends to destroy the structure.

An eroded berg may capsize due to reduced stability. For an Antarctic berg this is uncommon, although tiltmeter measurements show that some long narrow bergs roll with a very long period, implying marginal stability. In most cases an eroded Antarctic berg settles into a new orientation, tilted to some extent and thus exposing a new waterline for wave erosion. Large tabular icebergs also flex under the influence of long ocean swell, and in major storms may break up through flexural failure; the subunits have a bigger overall immersed surface area, and so melt more rapidly.

Distribution and Drift Trajectories

Freshly calved icebergs usually move westward initially, in the Antarctic Coastal Current. They may run aground and remain aground for years before moving on. Once the berg breaks away from the coast it comes under the influence of the Antarctic Circumpolar Current or West Wind Drift, the great eastward flowing current system that circles the globe in the Southern Ocean. Driven by wind and current the iceberg's track becomes easterly, but the Coriolis force due to the Earth's rotation also gives it a northward component. It is found that the breakaway from the coast tends to occur at four well-defined longitudes or "retroflection zones," situated in the Weddell Sea, east of the Kerguelen Plateau at 90° E, west of the Balleny Islands at 150° E, and in the northeastern Ross Sea. These are related to the partial division of the water south of the Antarctic Circumpolar Current into gyres (circulating current systems) such as the Weddell and Ross Sea gyres.

The berg's long northeasterly voyage can take it completely around the world, moving it far to the north of the Antarctic sea ice limit and even to the north of the Antarctic Polar Front. It is preserved by its high heat capacity, but it eventually reaches a low enough latitude to break up and melt. Under extreme conditions (e.g., if caught in a cold eddy), an iceberg may reach an unusually low latitude; the lowest recorded was 26°30′ S, 25°40′ W, off Brazil, while another low-latitude Atlantic sighting was in 1828, at 35°50′ S, 18°05′ E, where clusters of bergs of 30 m freeboard were observed.

Much work has gone into the modelling of iceberg drift, to derive drift velocity under known wind and current. An iceberg is acted upon by the frictional drag of the wind on its smooth surfaces (skin friction drag) and protuberances (form drag). The current acts upon its immersed surfaces, with the force changing direction with increasing depth (the so-called Ekman spiral). A large factor is the Coriolis force, which diverts icebergs to the left of their track in the Southern Hemisphere. This force is relatively stronger on icebergs than on sea ice (because icebergs have a larger mass per unit of sea surface area), so icebergs usually move more to the left of the wind than sea ice, typically some 40°–50° to the left, at about 3% of the wind speed. Short-term motions can seem quite bizarre. For instance, if a wind suddenly arises, a berg will initially describe loops (called inertial loops) before settling to a steady velocity.

Iceberg Scour and Sediment Transport

Just as sea ice can scour the seabed in shallow water, so an iceberg can plough a furrow several metres deep when it runs aground. Such scour marks have been known in the Labrador Sea and Grand Banks since the early 1970s, and in 1976 the first Antarctic marks were discovered in 16° W off the Dronning Maud Land coast of the eastern Weddell Sea. Later observations were made off Wilkes Land and Cape Hallett at the eastern entrance to the Ross Sea. Evidence indicates that long furrows are made when an iceberg is driven by sea ice, while freely floating bergs make only a short scour mark or a single depression. Apart from simple furrows, "washboard" patterns occur, created when a tabular berg runs aground on a wide front and is then carried forward by tilting and ploughing on successive tides. Circular depressions have also been seen, thought to be made when an irregular iceberg touches the bottom with a small "foot" and then swings to and fro in the current like a leaf in the wind. Such movement of a berg was actually observed off Cape Hallett. Grounding bergs have a deleterious effect on the seabed ecosystem, often wiping the seabed clear of all life.

Both icebergs and pack ice transport sediment in the form of pebbles, cobbles, boulders, and finer material, and even plant and animal life, thousands of miles from their source area. Antarctic bergs may carry stones and dirt on their underside, lifted from the glacier bed and later deposited out at sea as the berg melts; it is possible that most basal debris is melted off under the ice shelves. The presence of ice-rafted debris (IRD) in seabed sediment cores is an indicator that icebergs or sea ice occurred in the ocean at that location in a known era (given by the depth in the sediment at which the debris is found), and so is valuable as a way of mapping the distribution of icebergs, and thus of cold surface water, in past epochs such as glacial periods. The type of rock in the debris can also be used to identify the source region of the iceberg that dropped it.

It is ice-rafted plant life that gives the occasional exotic colour to an iceberg. Bergs are usually white (the colour of snow or bubbly ice) or blue (the colour of glacial ice, which is relatively bubble-free). A few deep green icebergs are seen in the Antarctic; it is believed that these are formed by the freezing of seawater rich in organic matter onto the bottoms of the ice shelves from which the icebergs later calved.

Climatic Role

Apart from local effects such as the production of fog, icebergs have two potential climatic roles. One is the effect of iceberg production on the mass balance of the parent ice sheets, and the other is the effect of their melt on the ocean.

The volume of the Antarctic Ice Sheet is 28 million km^3, which represents 70% of the global stock of fresh water, including groundwater. The mass balance is maintained by gain from snowfall balanced by loss from melting under ice shelves and calving of icebergs; contributions from summer runoff and from surface sublimation are negligible. Estimates of annual snowfall over the Antarctic continent are about 2000 km^3, so if the Antarctic Ice Sheet is in neutral mass balance the iceberg flux must be no greater than this value. Estimates of iceberg flux do start at this value, but some run much higher. Such fluxes, while huge, are less than the flow rate of the Amazon River (5700 km^3 per year). It is significant that the annual loss of ice from the ice sheet amounts to only one ten-thousandth of its mass, so that it constitutes an enormous passive reservoir. Global warming could lead to a greater rate of loss from this reservoir by iceberg calving and ice shelf melting, which would make an increased contribution to global sea level rise. At present the retreat of small subpolar and mountain glaciers is believed to contribute about 50% to the rate of rise, the rest being due to thermal expansion as the ocean warms.

Another effect of iceberg melt upon the ocean is freshening. The total Antarctic melt adds 0.1 m of fresh water per year to the surface water south of the Convergence. This dilution, if averaged over a mixed layer 100–200 m deep, amounts to 0.015–0.03 parts per thousand of salt. Melting icebergs thus make a small but not negligible contribution to maintaining the Southern Ocean pycnocline (the density boundary separating low-salinity surface water from higher-salinity deeper water), and to keeping surface salinity in the Southern Ocean to its observed low value of 34 parts per thousand or below in summer. If iceberg flux were to increase significantly due to global warming, this contribution would itself increase, and the Southern Ocean would become more strongly stratified.

An annual production of 1000 km^3 of Antarctic iceberg ice is about one-tenth of the annual production of Antarctic sea ice. Icebergs therefore make up a not insignificant fraction of the total volume of floating ice in the Antarctic. Sea ice has a neutral overall effect on ocean salinity, but an important differential effect, in that it increases ocean salinity where it forms (often near the coast), encouraging convection and bottom water formation, and decreases ocean salinity where it melts (often much further north in the Southern Ocean). Icebergs, on the other hand, always exert a stabilising effect on the water column, but only when they melt, which tends to be at lower latitudes rather than near the Antarctic coast where deep-water formation takes place.

Iceberg Detection and Destruction

Icebergs in the open sea produce squealing, popping, and creaking sounds due to mechanical stresses and cracking, which can be heard underwater up to 2 km away. In summer, bergs produce a high-pitched hissing sound called "bergy seltzer," due to the release of high-pressure air bubbles from the ice as it melts in the warmer water. In principle, therefore, icebergs can be detected by sonar. However, commercial ships rely on visual observation or radar. A decaying iceberg poses an additional danger to shipping because of its trail of growlers and bergy bits. Although small in size, they have masses (up to 120 tonnes for growlers; up to 5400 tonnes for bergy bits) which are capable of damaging or sinking ships. Furthermore, as they drop into the sea they often roll over, losing their snow layers to leave a smooth surface of wetted ice that offers a low radar cross-section in a heavy sea and that is visually hard to discriminate against foam and whitecaps. It is often the undetected growler or bergy bit that sinks a ship while the larger parent berg is detected and avoided.

Icebergs were responsible for the disappearance of many ships off Cape Horn during the windjammer era, and a new threat exists today. Large container ships, unable or unwilling to use the Panama Canal, can reach high southern latitudes on great circle transits from Australasia to Cape Horn. No special measures exist to protect such vessels, unlike in the North Atlantic where the International Ice Patrol was established in 1913 following the loss of the *Titanic* in April 1912. It keeps a continuous plot of the known or estimated location of every berg in the danger area, transmitted twice a day to shipping. Ships and aircraft are used for detection, aided today by satellite image interpretation, especially synthetic aperture radar (SAR), which combines high resolution (of order 20 m, capable of resolving most bergs) with day-and-night weather-independent capability. The latest generation of SAR, such as the Canadian Radarsat and the European Envisat, survey wide swaths (up to 450 km) in every orbit and so are capable of surveying the entire danger zone once per day.

During the 1950s–1960s, the US Coast Guard attempted to fragment dangerous icebergs. All methods were unsuccessful, especially explosives, since ice and snow are so effective at absorbing mechanical shock that the yield of fragmented ice was often no greater than the mass of explosive used. Recently it was found that very cold ice, such as in the lower part of an iceberg, can be fragmented successfully by the use of slow-burning explosives such as thermit, which can be implanted by drilling, itself a dangerous process because of the possibility of capsize.

Iceberg Utilisation

The immense amount of fresh water in an iceberg has inspired consideration of its use as a water source. Captain James Cook and other Southern Ocean explorers recovered iceberg ice directly for their ships; Cook stated that "this is the most expeditious way of Watering I ever met with." However, the earliest use of natural ice was as a refrigerant, before the days of industrial refrigeration. The Romans cut ice from Alpine lakes and transported it in straw to Rome, but ice use became more important in the nineteenth century in Europe and North America with their growing city populations and the need to transport and preserve perishable food like fish. Ice was cut from lakes, or exported from glaciers in Norway and Alaska by ship. In Alaska this continued until the 1950s. The first recorded instance of iceberg towing was the export of small icebergs from Laguna San Rafael in southern Chile to Valparaiso and Callao as part of a refrigerating ice supply business.

The idea of using iceberg ice for drinking or irrigation began with a suggestion by John D. Isaacs of Scripps Institution of Oceanography in 1949. He sought to relieve California's water shortage by towing icebergs from Alaska or Antarctica. No suitable technology existed, but during the 1960s iceberg towing evolved in the Labrador Sea, for protecting oil rigs. It was found that a floating bridle around the berg, attached to several tugs, was feasible and safe. This inspired a revival of Isaacs' idea in the form of further studies and two major conferences, at Ames, Iowa, in 1977 and in Cambridge, UK, in 1980. A stimulant was governmental interest by Saudi Arabia, which sought an alternative to expensive desalination.

The conclusions were that unprotected icebergs melt when towed through equatorial waters, and no viable insulation method existed. Therefore the destination must be in the same hemisphere as the source. The ideal site should have cold surface water and favourable currents along the towing route; deep water close inshore to permit nearshore mooring; and a serious local need for irrigation or drinking water. For Antarctic bergs this suggests three regions:

1. The Atacama Desert coast of northern Chile and southern Peru, with the cold northward-flowing Humboldt Current and a narrow shelf (less than 20 km in places). Irrigation could enormously increase agricultural productivity, as achieved in the past by the Mochicas.
2. The Namib Desert region of southern Angola, Namibia, and South Africa. Here there is cold upwelling near shore, a narrow shelf, and a coastal desert, the so-called Skeleton Coast. Suitable icebergs would come from the Weddell sector.
3. Western Australia and the Great Australian Bight. This is close to the Antarctic Circumpolar Current; there are places such as Rottnest Island off Perth where deep water reaches close inshore, and there is a need for drinking water for the expanding cities of Perth and Fremantle, which depend on groundwater. Suitable icebergs might be found near the Amery Ice Shelf.

The technology of finding, harnessing, and towing an iceberg involves many serious problems. For each destination there is an optimum source zone that involves minimal towing times. Icebergs that are already far north are usually in an advanced stage of melt, so younger bergs might be preferred. Even the most powerful tugs only modify the iceberg's drift by adding 1–2 knots of towing speed, so understanding of iceberg dynamics is essential in determining source area and towing strategy. Icebergs can be located by SAR imagery, so it will be possible to inspect several bergs until a suitable one is found. Towing will be by a number of powerful tugs attached to a floating bridle, with some danger of berg fracture under swell action. Assuming that the iceberg can be delivered to a coastal site, it must be anchored offshore and then reduced rapidly to pieces small enough to be towed ashore, melted, and processed.

The final stage is to make use of the iceberg fragments. Here an attractive idea is to make use of the latent heat of fusion of ice (330 kilojoules per kilogramme) to derive energy from the iceberg as well as water. The concept is called Icetec or ITEC, and a plan was developed for Saldanha Bay in South Africa. The iceberg fragments are towed into a storage basin created in the inner bay and separated from the main bay by a lock. Here the fragments melt, and the melt water is fed into an ammonia heat exchanger as used in ocean thermal energy conversion (OTEC) schemes. The warm Saldanha Bay water (20°C) fed into the seaward side evaporates the ammonia, which drives a turbine and is then condensed by iceberg meltwater. The warmed meltwater is fed back to the iceberg pool to enhance the melt rate of the bergs and to be cooled back to near freezing point. Some of the meltwater is drawn off for drinking or irrigation, sufficient to keep a constant level of water in the basin. It was estimated that the value of the electrical power is twice that of the water. Such a scheme could feed an agricultural complex with settlement and industry attached, or the electricity could be used to pump water to a more distant spot for use as drinking water. The idea is risky and requires huge initial investment, so no implementation has yet occurred. There are also international legal questions surrounding the free use of Antarctic icebergs.

PETER WADHAMS

See also **Antarctic Bottom Water; Antarctic Divergence; Antarctic Ice Sheet: Definitions and Description; Antarctic Intermediate Water; Antarctic Surface Water; Circumpolar Current, Antarctic; Coastal Ocean Currents; Continental Shelves and Slopes; CryoSat; Eddies in the Southern Ocean; Filchner-Ronne Ice Shelf; Firn Compaction; Glaciers and Ice Streams; Ice Sheet Mass Balance; Ice Shelves; ICESat; Lambert Glacier/Amery Ice Shelf; Larsen Ice Shelf; Marginal Ice Zone; Pack Ice and Fast Ice; Polar Front; Remote Sensing; Ross Ice Shelf; Southern Ocean; Southern Ocean: Bathymetry; Southern Ocean: Vertical Structure; Thwaites and Pine Island Glacier Basins**

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ICESAT

ICESat (Ice, Cloud, and Land Elevation Satellite) is a NASA Earth observation satellite launched in January 2003. The primary purpose of ICESat is to determine the mass balance of the Greenland and Antarctic Ice Sheets and floating ice shelves by measuring small changes in surface elevation with an accuracy better than 1 cm/year averaged over 100 km by 100 km areas. Changes in the ice mass, which are caused by differences between the mass input from snow accumulation and the mass output from iceberg discharge and melting, are calculated from the measured elevation changes. ICESat data is being used to determine the present-day mass balance of the Antarctic Ice Sheet and its contribution to global sea-level rise, and to study the relationships between ice changes and changes in polar precipitation, temperature, cloudiness, and other factors. Comprehensive satellite measurements are needed because the ice balance and the processes that influence mass changes undergo interannual and decadal variations, as well as longer-term changes.

Other scientific objectives of ICESat include measurement of sea-ice freeboard height for estimation of sea ice thickness, global measurement of cloud heights, and the vertical structure of clouds and aerosols; precise measurement of land topography and vegetation canopy height, and measurement of surface reflectivity.

The only instrument on ICESat is the Geoscience Laser Altimeter System (GLAS), which is the first laser altimeter on an unmanned Earth-orbiting spacecraft. GLAS emits a laser beam at 1064 nm to measure the elevation of Earth's surface and the heights of dense clouds and a second beam at 532 nm to measure the vertical distribution of thin clouds and aerosols. The distance from the satellite to the surface is measured to an accuracy of 3 cm, and the position of the satellite above the Earth ($\sim$600 km) is determined to 3 cm using global positioning system (GPS) receivers. Star-trackers on ICESat enable footprint locations on the surface to be calculated to 6 m horizontally. The resulting accuracy of the ice surface-elevation measurements is 20 cm averaged over 70 m diameter laser footprints spaced at 172 m along the track. The coverage of ICESat extends from 86° N to 86° S and the repeating ground tracks of the measurements lie within about 200 m of each other.

ICESat was designed to operate continuously for 3 to 5 years, but laser problems have limited the measurements to three observation periods a year for about 5 weeks each. By the end of 2005, ICESat acquired enough data to produce the most accurate surface elevation map ever made of Antarctica, to detect changes in surface elevations, and to map detailed ice features including: surface undulations, ice-shelf rifts, ice rises, ice fronts, and ice flowlines. The first ICESat is expected to be followed by an advanced ICESat mission to measure ice changes over at least 15 years. Additional information on ICESat can be obtained at http://icesat.gsfc.nasa.gov and data can be obtained from http://nsidc.org/daac/icesat/.

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See also **Antarctic Ice Sheet: Definitions and Description; Clouds; Ice Sheet Mass Balance; Ice Shelves; Precipitation; Remote Sensing; Temperature**

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IMPERIAL TRANS-ANTARCTIC EXPEDITION (1914–1917)

After Roald Amundsen and Robert Falcon Scott had reached the South Pole, Sir Ernest Shackleton, who had so nearly attained it on the British Antarctic Expedition (1907–1909), still saw the Antarctic as the place in which to win fame and fortune. He needed an ambitious project to capture the imagination of the public and potential sponsors. Crossing the continent of Antarctica fitted the bill. Such an expedition had been proposed in 1908 by the Scottish Antarctic scientist William Speirs Bruce, but he had been unable to raise sufficient funds. The German Wilhelm Filchner had also planned a crossing but only got funds for an expedition into the Weddell Sea.

Shackleton took over Bruce's scheme with the latter's approval. The exact details of the expedition were always hazy and subject to change, as was usual with Shackleton's plans. They were viewed with scepticism by several influential people, such as Shackleton's friend and later biographer Hugh Robert Mill. The official programme was extremely ambitious. Twelve men would be landed at Vahsel Bay (discovered by Filchner) at the bottom of the Weddell Sea, six of whom would make the 1800-mile (2900 km) crossing. They would sledge to the South Pole where the party would follow Shackleton's route from his previous expedition and emerge at McMurdo Sound in the Ross Sea region. A second team would set up base at McMurdo Sound and lay depots for Shackleton to pick up on his way northwards from the Pole. The crossing party would record geomagnetism, meteorology, glaciology, and geology. The remaining members of the Weddell Sea party would make additional journeys towards Graham Land (Antarctic Peninsula) and to Enderby Land. The ships would have programs of surveying coastlines and oceanographic work.

The expedition's two ships were *Endurance* and *Aurora*. The former was a wooden barquentine of 350 tons originally called *Polaris;* Shackleton chose the name *Endurance* from his family motto, "per ardua vincimus"—"By endurance we conquer." The name proved to be apt. *Aurora,* which would be used for the Ross Sea party, was purchased from Douglas Mawson who had used it on his Australasian Antarctic Expedition (1911–1914).

Unlike previous British expeditions, Shackleton planned to rely on dogs for transport and went to considerable trouble to obtain them. He arranged for the Hudson's Bay Company to send agents to buy 100 of the best dogs they could find in fishing villages on the shore of Lake Winnipeg. Equipment included dome tents designed for ease of erection and felt-lined canvas boots, which would become known as "Shackleton boots" although they were based on Amundsen's design. Shackleton also prepared innovative sledging rations that would be compact through the use of dehydrated foods and would prevent scurvy.

Finding funds for the expedition was a problem that required all of Shackleton's optimism and charm. The main backers were the Scottish cotton millionaire Sir James Caird, who contributed £24,000; Dudley Docker of BSA (British Small Arms), who contributed £10,000; and the British government, £10,000. Other significant donors included Dame Janet Stancomb Wills and Miss Elizabeth Dawson Lambton. Nevertheless, finances were always straitened, especially for *Aurora* and the Ross Sea party.

By contrast, staffing the expedition was simple. A report in a newspaper (not an advertisement as is popularly supposed) was followed by applications from more than 5000 men (and three girls). Fifty-six, including several Antarctic veterans, were chosen. Declaration of war on August 5, 1914, robbed the expedition of some personnel, and Shackleton offered the expedition and its ships to the British government, but Winston Churchill, First Lord of the Admiralty, replied with the telegram "Proceed." Shackleton joined *Endurance* at Buenos Aires and, because of reports of German naval activity off Chile, decided to head for South Georgia instead of the Falkland Islands. On reaching there on October 26, he learned from the Norwegian whalers that it was a bad year for pack ice; their recommendation was that he should delay departure. A month was spent modifying the structure of *Endurance,* acquiring stores from the whaling stations, training the dogs, and carrying out scientific work.

Eventually, *Endurance* set out for the Weddell Sea on December 5, and Coates Land was sighted on January 10. Then, with land in sight and only a short distance from their destination at Vahsel Bay, the ice floes closed in and the sea froze. *Endurance* was trapped and never escaped. At their farthest south, 77°00′ S, *Endurance* was formally declared a winter station and the ship's daily routine was abandoned. The ship began to drift northwards as scientific work and the training of men and dogs continued through the winter. However, from July onwards the ship began to experience bouts of pressure from the ice. On October 24, it began to leak, and two days later Shackleton gave the order to abandon ship. The complement set up Dump Camp on a large ice floe nearby.

Shackleton impressed upon his men that he would get them to safety if they would follow his orders. He also realised that he had to show clear, firm leadership, maintain a flexible approach, and preserve morale. However, given the uncertainties of their position, the best course of action was not easy to discern. The nearest settlements were the whaling stations at South Georgia and Deception, although there was a small Argentine station on the South Orkney Islands. Another option was to cross the Antarctic Peninsula to waters where whaling vessels operated in the summer. Paulet Island was a good staging post to the whaling stations because there was a stone hut built by the survivors of the Swedish South Polar Expedition's ship *Antarctic,* as well as stores left by their relief ship. (Shackleton was aware of this because he had been responsible for purchasing them and suggesting that they be left in the Antarctic for future use.)

To improve the chances of making a landfall, as well as to maintain morale, Shackleton ordered a march westwards across the ice floes. Progress was so slow that it was soon abandoned and Ocean Camp was established. It was near enough the wreck of *Endurance* for more stores and material to be recovered and a comfortable camp was established. *Endurance* eventually sank on November 21. A second attempt to move camp was made, but dragging sledges with three boats and their stores still proved backbreaking work. Six days and only 10 miles farther forward, another halt was called. Patience Camp was established without many of the amenities of Ocean Camp. The party now settled to wait until their northward drift brought them to open sea. Without the clockwise current, the Weddell Sea gyre, they would never have escaped. The dogs and Mrs. Chippy the cat were killed to save the meager food supplies. Seals and penguins were collected for food, but hunting became difficult as the floes broke up and floated loosely with open water between.

On April 9, 1916, the ice had dispersed sufficiently for the men to take to the three boats, named after the sponsors: *James Caird, Dudley Docker,* and *Stancomb Wills*. Paulet Island was no longer in reach, and Elephant Island and Clarence Island were the only options. The 7-day voyage that took them to a precarious landfall at Cape Valentine on Elephant Island was the most horrific part of the entire expedition. Sailing between ice floes that threatened to crush them and battered by stormy seas, the men suffered the miseries of seasickness, hunger, thirst, and soaking with freezing water. By the time they landed, some were at the end of their tether, but they could not stay at Cape Valentine to recuperate because the narrow beach backed by high cliffs would clearly be covered by storm surges. Frank Wild was despatched by boat to search for a better camping place and discovered a spit of land that became known as Point Wild. It was only just inhabitable but the expedition managed to survive there for 4 months.

Shackleton now determined to go for help, and the 22-foot (6.7 m) *James Caird* was prepared with a canvas and packing case decking, a stiffened keel, and an extra mast. On April 24, Shackleton set sail for South Georgia, 800 miles away. With him were Frank Worsley, captain of *Endurance* and skilled in both navigation and handling small boats; the carpenter "Chippy" McNish, whose skill had enabled the three boats to survive stormy seas to reach Elephant Island; Antarctic veteran Tom Crean; and two seamen, Timothy McCarthy and John Vincent. Taking advantage of a southerly wind, they headed northwards to clear the pack ice and then turned eastwards towards South Georgia. South America was nearer but they would have had to sail against the prevailing wind and current. The voyage to South Georgia took 16 days in indescribable conditions. The seas were stormy, on one occasion a giant wave nearly sank them; ice had to be chipped from the deck by men clinging tightly to the rigging; their clothes were not waterproof and, when off-watch, they lay in sodden sleeping bags on the rocks and bags of shingle used as ballast.

Salvation depended on Worsley's navigation, but there were very few occasions when he could take a sun-shot with his sextant. They made landfall at the western end of South Georgia but a storm blew up that nearly wrecked them on the cliffs of Annenkov Island before they made a landing on May 10 in Cave Cove on Cape Rosa, at the entrance of King Haakon Bay. Men and boat were unfit to sail around to the whaling stations on the north side of the island, so they had to cross the island. After a few days' rest, they moved to the head of the bay and turned *James Caird* upside-down for shelter at Peggotty Bluff.

Shackleton, Worsley, and Crean now set out on the final stage of their mission: the crossing of the unmapped interior of South Georgia. Although Stromness whaling station was only 22 miles (35 km) away, they had to cross glaciers and a mountain range equipped only with screws in their boots for crampons, an adze for an ice axe, and a length of rope. They were extremely fortunate with the weather and, with hardly a stop for food or rest, they reached Stromness in 36 hours.

The outside world was now aware of the plight of the 22 men stranded on Elephant Island, but rescue proved difficult. Four attempts were made to rescue them before the Chilean tug *Yelcho* found a way through the ice and reached Elephant Island on August 30. All the men were safe, having survived four months living in squalid, cramped conditions under the remaining two boats. Perce Blackborrow had his frostbitten toes amputated, and the health of some other men was deteriorating. The party was also running short of food.

Shackleton now turned his attention to the rescue of the Ross Sea party, which became known as "Shackleton's forgotten heroes." They had sailed from Hobart, Tasmania, on *Aurora,* and Aeneas Mackintosh had led a sledging party that established a depot at 80° S on February 20. *Aurora* was blown out to sea on May 6, taking most of the land party's supplies. It became trapped in heavy pack ice, the rudder was broken, and the ship drifted in the Ross Sea through the winter. When eventually released from the ice in February 1916, *Aurora* could only limp back to Port Chalmers, New Zealand.

Ten men had been left ashore and they wintered uncomfortably at Cape Evans, the base of Scott's last expedition. Conditions were improved by using food and equipment left by Scott's and Shackleton's earlier expeditions. On September 1, nine men and four dogs made an early start to lay more depots, the last being at Mount Hope (84° S). The Rev. Arnold Spencer-Smith died of scurvy and the remainder barely reached the safety of Hut Point. Impatient to get back to Cape Evans, Mackintosh and V. G. Hayward set off across newly formed sea ice. A gale blew up, the ice was swept out, and the men were never seen again. On January 10, 1917, *Aurora* returned with Shackleton on board, and the survivors were brought out to Wellington, New Zealand.

The Imperial Trans-Antarctic Expedition was a complete failure. None of its objectives had been achieved. Three men and one ship had been lost, as had such scientific specimens as had been collected. Nevertheless, the expedition was a "glorious failure," and the rescue of the complement of *Endurance* from the Weddell Sea has become one of the greatest epic stories of polar exploration, while Shackleton has become a paradigm for teaching leadership skills.

ROBERT BURTON

See also **Australasian Antarctic Expedition (1911–1914); British Antarctic *(Nimrod)* Expedition (1907–1909); Bruce, William Speirs; Filchner, Wilhelm; German South Polar *(Deutschland)* Expedition (1911–1912); Photography, History of in the Antarctic; Ross Sea Party, Imperial Trans-Antarctic Expedition (1914–1917); Shackleton, Ernest; South Georgia; Swedish South Polar Expedition (1901–1904); Swedish South Polar Expedition, Relief Expeditions; Weddell, Ross, and Other Polar Gyres; Weddell Sea, Oceanography of; Wild, Frank; Worsley, Frank**

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INDIA: ANTARCTIC PROGRAM

India got involved in scientific research in Antarctica under a joint Indo-Soviet agreement between the Indian Space Research Organisations (ISRO) and the Hydro Meteorological Services (HMS) of the USSR. Dr. Paramjit Singh Sehra became the first Indian ever to winter over the South Pole in the 17th Soviet Antarctic Expedition during 1971–1973 and carried out research related to upper atmosphere.

In 1981, the first Indian Scientific Expedition to Antarctica (ISEA) was launched under the leadership of Dr. S. Z. Qasim, whose team reached Antarctica on 9 January 1982. The decision to launch the expedition to Antarctica was taken by the government of India keeping the scientific, environment, geopolitical, and national interests in mind. Since then, annual Indian Antarctic expeditions (IAEs) have been launched without interruption; to date India has launched twenty-three expeditions. In addition, four special expeditions have also been launched: Weddell Sea Expedition; krill biology; Pilot Experiment for Southern Ocean (PESO), for integrated oceanography research of the Southern Ocean; and for observing the total solar eclipse in November 2003. Since the nineteenth IAE, the launching point has been shifted from Goa, India, to Cape Town, South Africa.

In 1983, India established its first permanent station, Dakshin Gangotri (70°45′ S, 11°37′ E), and the team wintered there to carry out scientific and logistic tasks. On 12 September 1983, India achieved the status of Consultative Party, on 1 October became a member of Scientific Committee on Antarctic Research (SCAR), and in 1986 became a member of the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR). In 1997 India also ratified the Protocol on Environmental Protection to the Antarctic Treaty thus reaffirming India's commitment to protecting the Antarctic environment. India hosted the eleventh COMNAP/SCALOP (Standing Committee on Antarctic Logistics and Operations) meeting at Goa in 1999, and the working group meeting on ecosystem monitoring and management of CCAMLR in August 1998 at Cochin. India occupied the CCAMLR chair beginning in November1998 for a period of 2 years.

In 1988–1989, India established its second permanent station, Maitri (70°46′ S, 11°44′ E), which is being used for scientific research. It is equipped with modern facilities to carry out research in various domains of polar science and can accommodate twenty-five wintering members. The summer huts around Maitri accommodate around forty-five summer team members. The research is focused towards understanding the role of Antarctica in the global climate system and its connections with monsoon and other large scale systems utilizing the data from ice core analysis, remote sensing, and other *in situ* observations. The disciplines range from microbial study to the evolutionary history of Antarctica, including human physiology and cold region adaptation, and cold region engineering and communication. The station is equipped with modern communication facilities, INMARSAT and HF Communications.

On 25 May 1998, India's Department of Ocean Development (DOD) established the premier polar research institute, the National Centre for Antarctic and Ocean Research (NCAOR), at Goa, to manage the entire gamut of polar activities by converting the erstwhile Antarctic Study Centre, an attached office of DOD. NCAOR has become a full-fledged research centre with world-class laboratory support, ice core repository, and analysis facility for palaeoclimate research. NCAOR also maintains the Sagar Kanya Ocean research vessel for oceanographic research in the country.

Expedition members are selected by NCAOR from throughout India by open advertisement and following a peer review process, after which they are finally approved by the Department of Ocean Development of the Government of India. The selected team members are medically screened by physicians from the prestigious All India Institute of Medical Sciences in New Delhi and given acclimatization training at Auli in the foothills of the Himalayas. Before departure to Antarctica, they are also briefed at NCAOR by experts in firefighting, survival, first aid, medical, team management, and environmental protection. The average expenditure per expedition is around Indian Rs. 200 million.

Currently there are more than seventy institutions in India that are involved in the Indian Antarctic Programme and the logistics are managed by Army personnel from the Ministry of Defense. Around 300 publications have resulted from Antarctic research by India. The web address for further information is http://www.nic.in.

PREM CHAND PANDEY

See also **Antarctic Treaty System; Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Protocol on Environmental Protection to the Antarctic Treaty; Remote Sensing; Russia: Antarctic Program; Scientific Committee on Antarctic Research (SCAR); South Pole**

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INSECTS

Insects are a monophyletic group of arthropods distinguished by three main body regions, the head, thorax, and abdomen, with the thorax bearing three pairs of legs and two pairs of wings, though the latter may often be reduced or absent. With 4–8 million extant species, they are thought to be the most diverse group of organisms on the planet, constituting as much as 70% of animal species richness. Although springtails are also characterized by three pairs of legs, and were once sometimes thought to be closely related to insects, they are regarded as sufficiently distinct to place them in a different group. In consequence, springtails are not discussed here. However, springtails are often included in discussions of the ecological roles of insects because they dominate the soil fauna, along with mites, especially in Antarctic systems. These two groups of arthropods are amongst the most significant soil animals in Maritime Antarctic and sub-Antarctic systems, and in some continental Antarctic sites such as Cape Hallett in northern Victoria Land. In other parts of continental Antarctica they are typically less speciose with lower abundances.

There are no free-living insects found in the continental Antarctic. Only ectoparasitic species, such as fleas and lice, which feed and typically remain on their seabird hosts, can be found here. These are also the most diverse group of insects found in the whole of the Antarctic region, and include seals among their hosts, too. However, there are three free-living species found in the Antarctic region, and they are all flies. *Belgica antarctica* is an indigenous, nearly wingless midge. Its larvae are found in a variety of habitats such as nutrient-enriched sites close to seal wallows and bird nesting areas, in detritus, in mosses and algae, and in cyanobacterial mats in seasonal melt streams, and it has a life cycle that extends over 2 years. Adult males and females are active only in the summer, and tend to be short-lived. This species is most closely related to *Eretmoptera murphyi,* which is endemic to South Georgia but was accidentally introduced to Signy Island (South Orkney Islands). Molecular clock data suggest that the two species are separated by tens of millions of years. In turn, they are separated from their closest ancestors by some 70 million years, suggesting that the biogeography of these species has been dominated by vicariance associated with the breakup of Gondwana. The third midge species found in the region is the winged *Parochlus steinenii*. This species is found on the maritime Antarctic South Shetland Islands and as far north as sub-Antarctic South Georgia, Tierra del Fuego, and the Andes in southern South America. Although thought to be a possible introduction by humans to the region, sequence data indicate a divergence time of 7.6 million years between populations on South Georgia and the South Shetland Islands, indicating natural colonization. The only other insects found in Antarctica are introduced species that typically do not live for long or reproduce outside of the occupied stations on the continent. Most noteworthy amongst these is a small population of *Lycoriella* sp. (Sciaridae) established in the sewage processing system of Casey Station (East Antarctica), and another in the bond store of Rothera Station (Antarctic Peninsula).

On the sub-Antarctic islands there is a greater diversity of indigenous species, typically increasing with incoming levels of solar radiation and to some extent with greater plant species richness, which in turn is associated with increasing island area. Islands to the north usually have greater species richness than those to the south. The importance of energy in determining species richness is becoming increasingly well appreciated globally, and the Antarctic region is not an exception in this regard. Nonetheless, the insect faunas have long been thought of as disharmonic. That is, there are many orders that are missing from the island faunas by comparison with similar continental sites. Thus, the flies (Diptera) and beetles (Coleoptera) predominate in terms of species richness, although some islands are also home to one or two moth (Lepidoptera), bug (Hemiptera), and parasitic wasp (Hymenoptera) species. By contrast, orders such as the bristletails (Archaeognatha), dragonflies (Odonata), mayflies (Ephemeroptera), cockroaches (Blattodea), mantids (Mantodea), stoneflies (Plecoptera), and antlions (Neuroptera) are missing, and groups typical of most systems, such as butterflies, bees, and ants, are also conspicuous by their absence. This disharmony is attributed to the isolation and cold climates of the islands, which might explain the fact that the idiosyncratic nature of the faunas is less pronounced for many of the more temperate Southern Ocean islands and those that lie closer to continents (e.g., Auckland, Campbell, Falkland islands). On the sub-Antarctic islands, the most widely distributed species are the beetles *Palirhoeus eatoni* (Curculionidae), *Meropathus chuni* (Hydraenidae), and *Halmaeusa atriceps* (Staphylinidae), the moth *Embryonopsis halticella* (Yponomeutidae), and the flies *Anatalanta aptera* (Sphaeroceridae) and *Apetaenus litoralis* (Tethinidae). The distribution patterns of the insects do not form highly nested subsets, suggesting that the origins of most of the species are from the continents closest to the island or archipelago in question. However, the biogeographic origins of many of the groups, such as the *Ectemnorhinus* group of weevils, remain a mystery.

Herbivory and detritivory are common amongst insects of the Antarctic region, with predation and parasitism being rarer. Amongst the herbivores, several are noteworthy because they consume algae, lichens, mosses, and liverworts. Lichen and bryophyte feeding is uncommon amongst insects in general, which usually prefer angiosperms. However, weevils in the sub-Antarctic region predominantly feed on cryptogams, with angiosperm herbivory being rarer. It is thought that these strategies evolved in response to the paucity of angiosperms, but abundance of cryptogams, during the Quaternary glaciations. One of the most unusual of these weevils is *Palirhoeus eatoni,* which is an intertidal to supra-littoral species specializing on algae and their lichenized forms. Both larvae and adults are tolerant of a wide variety of osmolalities associated with life on rocks that are inundated both by seawater and by rain. Detritivores are thought to be especially important for nutrient cycling in vegetated terrestrial areas on the sub-Antarctic islands, and larvae of the tineid moth, *Pringleophaga marioni,* are considered keystones that form the bottleneck to nutrient cycling at the Prince Edward Islands. The larvae of this moth species benefit from high temperatures of occupied wandering albatross nests and are more abundant here than elsewhere on the islands. Albatrosses thus serve as thermal ecosystem engineers for these caterpillars. Predation is restricted to a small number of carabid and staphylinid beetle species, which prey on springtails, weevil larvae, and occasionally spiders. In turn, spiders, lesser sheathbills *(Chionis minor),* and kelp gulls *(Larus dominicanis)* are the chief predators of insects. Sheathbills are especially reliant on insects for winter survival, while in summer they forage amongst seabird colonies and seal haul out areas. Amongst the insects, parasitism is perhaps the rarest lifestyle, with only a single recorded parasitoid species, the wasp *Kleidotoma icarus,* which parasitizes the fly *Apetaenus litoralis* on the Prince Edward Islands and Îles Crozet. Unlike the Arctic regions, pollination by sub-Antarctic insects appears to be absent and indeed there are very few obviously entomophilic flowers in the sub-Antarctic. Whether insect-pollinated flowers are absent because of an absence of pollinators or vice versa is not clear, and it is a topic that has enjoyed comparatively little attention in the region.

The majority of Antarctic and sub-Antarctic insects are freezing tolerant although several species are freeze intolerant. That is, they are able to survive the formation of ice in their tissues (although ice formation within the cells has not been documented in these species). However, they tend to be moderately so, such that the temperature at which they die is only a few degrees lower than the temperature at which they freeze. The preponderance of moderate freezing tolerance appears to be a feature of the Southern Hemisphere because it is true also of insects from New Zealand, South America, and the alpine regions of southern Africa. In the Northern Hemisphere, most species tend to be freeze intolerant, though in the highest Arctic regions the majority of species are strongly freezing tolerant such that they can survive many degrees of freezing. It is thought that the mild subzero temperatures of much of the southern temperate zone, which mean that temperatures fluctuate around the freezing point, and the likelihood of summer cold snaps and winter thaws are all factors that have promoted moderate freeze tolerance. This strategy effectively means that insects do not have to engage in the protracted biochemical preparation that typically precedes freeze avoidance, but can resist moderate freezing at any time. Indeed, it has been shown that moderately freeze-tolerant caterpillars of the tineid moth, *Pringleophaga marioni,* can survive repeated freeze-thaw events with little ill effect, although long-term cold inhibits their growth.

Low growth rates over multiple seasons are common to many Antarctic and sub-Antarctic insects. Indeed, the overall life history strategy of these species can be considered flexible, with little seasonality and few records of true cue-mediated diapause. Life cycles typically last for a year or longer, with the longest being that of the moth *Pringleophaga marioni* (>5 years). Nonetheless, there are peaks in activity in some species, such as the summer activity of the Maritime Antarctic species *Belgica antarctica,* the spring emergence of adult *Ectemnorhinus similis* weevils, and the distinct mid-summer emergence of the fly *Calycopteryx moseleyi* (Micropezidae), a species closely associated with the Kerguelen cabbage *(Pringlea antiscorbutica)*. Seasonality also appears to be more typical of species occupying southerly sites. For example, there is distinct seasonality and synchronization of emergence in the same species on the colder Heard Island by comparison with those from warmer Marion Island. These differences in seasonality between the islands are also responsible for opposite altitudinal size clines among weevil species on the islands. On Heard Island, body size within a species typically declines with altitude owing to the declining in growing season with increasing elevation. On Marion Island, the opposite is found. Increases in size with declining temperature in relatively aseasonal environments are common in many insect species. In general, Antarctic insects respond most strongly to the abiotic environment that, along with plant community type, appears to have a substantial influence on assemblage composition. By contrast, horizontal (i.e., competitive) interactions are rare, and restricted to *Amblystogenium* ground beetles on Possession Island, and perhaps to rock face-dwelling weevils on the other South Indian Ocean Province Islands.

Many insect species have been unintentionally introduced to the Antarctic region and have survived there. On the continent such species are restricted to scientific stations, but further north they have established and invaded many islands. The most widespread alien invasive species are the fly *Psychoda parthenogenetica* (Psychodidae), the aphid *Rhopalosiphum padi,* and the thrip *Apterothrips apteris* (Thripidae). Most of the introduced species are of European origin, though some southern continental species have also invaded the islands. In addition, there have been several interisland transfers, such as of the carabid beetles *Trechisibus antarcticus* and *Oopterus soledadinus* from the Falklands to South Georgia and in the latter species also to the Kerguelen archipelago. Some purportedly indigenous species, such as the diving beetle *Lancetes angusticollis* (Dytiscidae) on South Georgia, may have been introduced by sealers and whalers before scientific documentation of the biotas began. The accidental nature of the introductions is reflected by the strong relationship between annual numbers of visitors to an island and the numbers of introduced insect species that have successfully established on an island, although islands with greater numbers of indigenous plant species, and those that have greater incoming energy also support larger numbers of invasive alien insects. In some cases, ameliorating climates have only recently made certain islands susceptible to colonization by alien species. For instance in the case of the fly *Calliphora vicina* (Calliphoridae), climate warming at Kerguelen has meant that the islands only became habitable for the species in the mid-1980s.

The effects of invasive alien species have been investigated at only a few sites. On South Georgia, the invasive ground beetle, *Trechisibus antarcticus,* increased its range substantially during the 1990s. In those sites where it is present it has substantial direct and indirect effects on the indigenous perimylopid beetle *Hydromedion sparsutum* (Perimylopidae) At Kerguelen, the introduced carabid *Oopterus soledadinus* is having similar effects on indigenous species, whilst the introduced fly *Calliphora vicina* is thought to be responsible for a decline in the abundance of an indigenous competitor, *Anatalanta aptera*. On Marion Island, larvae of the introduced midge *Limnophyes minimus* (Chironomidae) reach considerable densities in a variety of waterlogged communities. It has been suggested that they increase nutrient turnover substantially in these habitats as a consequence of their activity. A further effect of introductions is to increase trophic complexity on the islands. For example, on Marion Island, introduced *Rhopalosiphum padi* aphids are now being parasitized by an introduced *Aphytis* wasp, so effectively adding another trophic level that was previously absent in lowland vegetation communities. Several recent studies have also raised concerns about negative interactions between indigenous and alien species that will be precipitated by climate change. The invasive alien species typically have rapid life cycles and many of them are parthenogenetic. They show strong physiological (e.g., growth and development) response to increasing temperature. By contrast, indigenous species usually have long life cycles, and are not particularly fecund. Moreover, they respond more weakly to elevated temperature (i.e., they have shallow rate-temperature curves). In consequence, it seems likely that with the increases in temperature that are being documented in many parts of the Antarctic region, invasive alien species will be at an advantage, at least from a life history perspective. What this means for ecosystem dynamics and functioning is presently not clear.

Introduced rodents also pose a threat to the insects indigenous (and in many cases restricted) to the Antarctic region. On several islands, insects constitute the dominant food source for house mice, *Mus musculus (sensu lato),* and insects are also consumed by rats on other islands. House mice are thought to be responsible for the marked differences in insect abundances between Marion Island and the nearby, mouse-free Prince Edward Island, as well as substantial declines in body size of weevils on the former but not the latter island. The mice are also responsible for more than an order of magnitude decline in the biomass of larvae of the indigenous tineid moth *Pringleophaga marioni* between the late 1970s and late 1990s. By consuming these larvae, mice are also thought to be substantially altering nutrient cycling at the island, and this is expected to intensify as mouse numbers increase in response to warming, precipitated by global climate change. Moreover, mice have also indirectly affected lesser sheathbill numbers by consuming invertebrates, which form the major winter food source of this bird. Indirect effects of other introduced species have also been documented. For example, reindeer on South Georgia are thought to be affecting the body size of the indigenous beetle *Hydromedion sparsutum,* by altering the availability of high quality food sources such as the tussock grass, *Parodiochloa flabellata*.

Antarctic and sub-Antarctic entomology has had a venerable history. Among the early taxonomists and collectors who have worked on the region's fauna are H. N. Moseley (of the *Challenger* Expedition), G. R. and C. O. Waterhouse (a father and son), and C. Eaton, G. Enderlein, R. Jeannel, J. L. Gressitt, L. Brundin, P. J. Darlington Jr., Ph. Dreux, and G. Kuschel. The midges of the Crozet Islands and southern continents formed the subject of a long and heated debate between Brundin and Darlington concerning the importance of dispersal versus vicariance in the region. Today it is clear that both processes are important, though phylogeographic and molecular systematic work has demonstrated that dispersal is perhaps more common than previously thought. Although systematic work, and especially molecular approaches to the subject, continue on the insects of the Antarctic, much work is now focussed on ecology, physiological responses, and increasingly the genomic underpinnings of these functional responses. Antarctic ecosystems and their insect inhabitants are thought to be model systems for understanding the likely outcome of interactions between indigenous and invasive species under a climate of environmental change.

STEVEN L. CHOWN

See also **Albatrosses: Overview; Algae; Antarctic Peninsula; Auckland Islands; Biogeography; Campbell Islands; *Challenger* expedition (1872–1876); Cold Hardiness; Colonization; Crozet Islands (Îles Crozet); Flowering Plants; Gondwana; Heard Island and McDonald Islands; Kerguelen Islands (Îles Kerguelen); Lichens; Liverworts; Mosses; Parasitic Insects: Lice**

and Fleas; Parasitic Insects: Mites and Ticks; Prince Edward Islands; Sheathbills; South Georgia; South Orkney Islands; South Shetland Islands; Springtails

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INTERNATIONAL CONVENTION FOR THE PREVENTION OF POLLUTION FROM SHIPS (MARPOL)

The International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto (MARPOL 73/78) regulates the prevention of deliberate, negligent, or accidental pollution of the marine environment from ships. It emerged largely in response to the increasing number of oil tanker pollution incidents during the 1960s and 1970s (in particular the *Torrey Canyon* grounding in the English Channel in 1967) and the recognition that pollution from the routine operation of vessels was a greater threat to the marine environment than catastrophic accidental releases.

The convention combines two international treaties adopted in 1973 and 1978 and a number of amendments adopted piecemeal since then. It has six technical annexes:

Annex I	Regulations for the Prevention of Pollution by Oil
Annex II	Regulations for the Control of Pollution by Noxious Liquid Substances in Bulk
Annex III	Prevention of Pollution by Harmful Substances Carried by Sea in Packaged Form
Annex IV	Prevention of Pollution by Sewage from Ships
Annex V	Prevention of Pollution by Garbage from Ships
Annex VI	Prevention of Air Pollution from Ships

Annex I of MARPOL 73/78 entered into force on October 2, 1983. Today, 128 countries are signatory to Annexes I and II of the Convention. States signing up to the convention must accept Annexes I and II, which include strict regulations for ship design. However, they may choose whether to accept the optional Annexes III, IV and V. Annex VI was adopted in September 1997, but has yet to come into force.

The Secretariat of MARPOL 73/78 is based within the International Maritime Organization (IMO), London.

In 1990, the Marine Environment Protection Committee (MEPC) of the IMO recommended that the Antarctic (defined as the sea area south of latitude 60° S) be given the highest level of protection as a Special Area relating to Annex I (Oil) and Annex V (Garbage). This amendment formally entered into force on March 16, 1992.

Under Annex I of MARPOL 73/78, the discharge of oil or oily mixture from any ship in the Antarctic Area is prohibited, except in accordance with stringent conditions on processed bilge water, or in cases of emergency. Oil or oily wastes must be stored on board vessels and discharged at Port Reception facilities outside the Antarctic Area.

Similarly, under Annex V of MARPOL 73/78, the disposal into the sea of all garbage (including plastic) other than food waste, is prohibited. Port states which are party to the convention are required to provide adequate facilities to receive garbage. Disposal of food wastes into the sea is prohibited less than 12 nautical miles from the nearest land.

Annex IV of the Environmental Protocol largely mirrors Annexes I, IV, and V of MARPOL 73/78, although there are a number of minor differences. Where the specific provisions of Annex IV are weaker than MARPOL 73/78, Article 14 states that "With respect to those Parties which are also Parties to MARPOL 73/78, nothing in this Annex shall derogate from the specific rights and obligations thereunder."

Rod Downie

See also **Antarctic Treaty System; Operational Environmental Management; Pollution; Protocol on Environmental Protection to the Antarctic Treaty**

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INTERNATIONAL GEOPHYSICAL YEAR

The International Polar Years 1882–1883 and 1932–1933 contributed a little to knowledge of the Antarctic region but nothing about the continent itself. By 1950 it was felt that scientific and technical advances justified a third polar year, with particular attention to the south. The idea took shape at a dinner given by James van Allen, an American expert on the use of rockets for high-altitude research, in honour of the British geophysicist Sydney Chapman, FRS. The suggestion was passed to the Commission on the Ionosphere and forwarded enthusiastically to the International Council of Scientific Unions (ICSU), which formally accepted it in 1951.

In response to protests from meteorologists and geomagnetists, the programme was widened and named the International Geophysical Year (IGY). The subjects were to include the aurora, cosmic radiation, geomagnetism, glaciology, gravity, ionospheric physics, meteorology, and seismology. Cartography, geology, oceanography, and biology were not included. The scope was worldwide, but Antarctica was to receive special attention because of previous neglect and its unique features, such as the wide separation of its geographic, magnetic dip, and magnetic invariate poles. Work was also to be done in the Arctic, with establishment of links by three pole-to-pole meridians along which to record phenomena such as air circulation, electric activity in the stratosphere, and magnetic fields in space. A Comité Special de l'Année Geophysique Internationale (CSAGI) was set up to plan programmes and invite participation. The IGY was planned to run for 18 months to ensure adequate sampling of data and to span an expected peak of sunspot activity. From CSAGI's general programme, detailed plans were passed on to national IGY committees and organisations selected to carry out the work.

By May 1954, twenty nations had agreed to cooperate. The United States, through its National Academy of Sciences and National Research Council, with the Department of Defense supporting the placing of scientists and their equipment in remote locations, made the greatest contribution, but could not dictate to others. At this stage, the Cold War was still on; the Soviet Union was not a member of ICSU and had not suggested participation. However, Stalin had died the previous year, and Soviet scientists began to fraternise with colleagues in other countries. A CSAGI meeting in Rome in 1954 proved crucial when it was notified by the Soviet Embassy that the Soviet Academy of Sciences would send representatives. It joined ICSU but political disputes threatened. Since the USSR had hitherto shown no interest in the Antarctic land-mass, there was surprise when establishment of three stations was announced, one at the South Pole, where, as they presumably knew, the US had decided to place one. Fortunately, their representatives, led by Vladamir Beloussov, a distinguished, serious, but reasonable expert on tectonics, accepted that there was an enormous gap in central East Antarctica and agreed to put the station there, at the Pole of Inaccessibility, instead.

Argentina and Chile had sent ambassadors, not scientists, and both Chinas wanted to participate but neither would tolerate the other's presence. Amicable settlements were largely due to Colonel Georges Laclavere, chairman of CSAGI, whose forceful resolve to put science before politics set the tone for the meetings. Agreement that there should be exchange of personnel between national stations helped greatly.

When things began, on 1 July 1957, the IGY included scientists of sixty-four nationalities involving 4000 stations, those in Antarctica numbering fifty-five from twelve countries (Argentina, Australia, Belgium, Chile, France, Japan, New Zealand, Norway, South Africa, the United Kingdom, the United States, and the USSR). The Sun began proceedings precisely on time with a major flare accompanied by a spectacular auroral display and disruption of communications worldwide. Shortly after that, the USSR launched Sputnik I to the consternation of the US, which then put increased effort into rocket and satellite development, much to IGY's benefit. Explosions were fired at different heights and ionospheric measurements were recorded in experiments described as some of the greatest ever conducted in pure science. Although having no intended relation with Antarctica, the results were later welded in with magnetic observations, mainly from the Antarctic, to produce a magnificent concept of the entire magnetosphere. Apart from this, a programme of three World Days per month for intensive observations in related disciplines was agreed, and there were also periodic 10-day Meteorological Intervals. Data were to be freely exchanged and World Data Centres, each having a complete set, were established in the US, the USSR, and a third jointly between western Europe, Australia, and Japan.

The Commonwealth Trans-Antarctic Expedition led by Vivian Fuchs and Edmund Hillary was contemporary with the IGY but not part of it, although interacting, carrying out gravity determination and seismic soundings, and being a means of involving the reluctant New Zealand with the IGY.

The cost of the IGY, around US$280 million, was carried mostly by the US and the USSR. Reports, filling forty-eight volumes of the *Annals of the International Geophysical Year,* appeared between 1957 and 1967. At the end of the IGY, the USSR decided to maintain its status in the Antarctic, and the US was certainly going to stay if this were so. Other countries wanted to get footholds as well. An unexpected outcome was improvement in international relations. Politicians had the acumen to realize that IGY scientists had worked together harmoniously regardless of hostilities between their respective governments. In 1961 the Antarctic Treaty came into force, shelving territorial claims for an indefinite period and setting the Antarctic aside for scientific purposes. It was becoming accepted that heavy cargo planes as well as ships could link Antarctica with the rest of the world, and research stations could be established more easily. Without immediate prospect of commercial exploitation and with the Treaty's ruling that all research results should be common property among the nations, there was no incentive for governments to dictate the course of research, and scientists were largely free to follow their own interests. Biologists, envious of IGY success, entered into similar international cooperation, and under the auspices of ICSU devised the International Biological Programme, which ran worldwide for 10 years from 1964. Besides providing a model for other international arrangements, the Treaty has worked through the Scientific Committee on Antarctic Research (SCAR) to promote science and conserve the Antarctic wilderness

G. E. Fogg

See also **Antarctic Treaty System; Commonwealth Trans-Antarctic Expedition (1955–1958); Fuchs, Vivian; Geospace, Observing from Antarctica; Hillary, Edmund; History of Antarctic Science; International Polar Years; Russia: Antarctic Program; Scientific Committee on Antarctic Research (SCAR); United States: Antarctic Program**

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INTERNATIONAL GEOSPHERE-BIOSPHERE PROGRAMME (IGBP)

The International Geosphere-Biosphere Programme (IGBP) is an international research programme that studies the interactions between biological, chemical, and physical processes, and human systems. Its vision is to provide scientific knowledge to improve the sustainability of the living Earth.

IGBP is built on interdisciplinarity, networking, and integration. It addresses scientific questions where an international approach is the best or the only way to provide an answer, and adds value to a large number of individual, national, and regional research projects through integrating activities to achieve enhanced scientific understanding of the Earth system.

The Programme dates back to 1986 when the International Council for Science (ICSU) decided that an international collaborative research endeavour on the phenomenon of global change was required. The planning phase (1987–1990) involved about 500 scientists from around the world.

Implementation began with the official launch of five projects in 1990, and an additional five projects were launched during the 1990s. The projects have focused on different aspects of the Earth system: the hydrological cycle, terrestrial ecosystems, ocean fluxes, ocean ecosystem dynamics, atmospheric chemistry, land-ocean interactions in the coastal zone, land-use and land-cover change, past global changes, and global analysis, integration, and modeling. Infrastructural support is provided by the IGBP Secretariat in Stockholm, Sweden, established in 1989, and by project offices around the world.

In 1999 the Scientific Committee of IGBP, which guides IGBP research, launched a synthesis phase to assemble the key findings of the first decade of IGBP research, and to provide the foundation for the second decade of research. Several realisations emerged from the synthesis to guide the scientific planning for the second decade of IGBP research: the Earth is a complex system that life itself helps to control; the dynamics of the Earth system are characterised by thresholds and abrupt changes; the human enterprise drives multiple, interacting effects that cascade through the system in complex ways; global environmental change is much more than climate change and is happening now; and our planet is, in many respects, in a state far different from anything seen in the last half million years.

IGBP's Antarctica-related research has, to a large extent, focussed on synthesising available ice core data. Ice cores provide a record of the deposition of atmospheric chemicals to the snow through time, with the most recent deposits being at the top of the ice core, and the oldest at its base. One example of research on ice core data focuses on mineral aerosols, which are soil particles suspended in the atmosphere in arid regions with strong winds (for example North Africa). Some of these particles are transported very long distances and are deposited in the ice sheets. Ice core records go back over 400,000 years and show large variations with time. Colder periods, such as ice ages, tend to have much greater (2–100×) concentrations of mineral aerosol particles than warm periods such as today. These higher deposition rates have been hypothesized to be caused by the decreased precipitation and carbon dioxide or strong surface winds in the source region. IGBP's projects GAIM (Global Analysis, Integration, and Modelling) and PAGES (Past Global Changes) have helped synthesize this and other information on the Earth's environment in the past to better understand the processes that control atmospheric carbon dioxide concentration between glacial and interglacial periods. Higher concentrations of mineral aerosols during the cold periods may have helped cool the Earth's surface, and may be partly responsible for the lower carbon dioxide levels during the colder periods.

By 2003 this synthesis phase was largely complete and phase II of the IGBP programme was launched, based on a new set of overarching scientific questions, and organised around a new structure with a focus on biogeochemical sciences with relevance to issues of societal concern, interdisciplinarity and integration, and Earth system context. The IGBP network now involves more than 2000 scientists from around the world, and has National Committees in seventy-eight countries. IGBP collaborates with various organizations and programmes, and is one of four partners in the Earth System Science Partnership (ESSP), which involves DIVERSITAS (An international programme of biodiversity science), IHDP (International Human Dimensions Programme on Global Environmental Change), and WCRP (World Climate Research Programme).

Sofia Roger and Kevin J. Noone

See also **Earth System, Antarctica as Part of; Ice Ages; Ice Core Analysis and Dating Techniques; Paleoclimatology; World Climate Research Programme (WCRP)**

Reference and Further Reading

IGBP Website: http://www.igbp.net

INTERNATIONAL POLAR YEARS

The First International Polar Year was the brainchild of Lieutenant Karl Weyprecht of the Austro-Hungarian Navy. As coleader of the Austro-Hungarian Exploring Expedition of 1872–1874, Weyprecht had wintered in the ice, on board *Tegetthoff,* off the southeast coast of Franz Josef Land (Zemlya Frantsa-Iosifa). On the basis of that experience, and of his thorough knowledge of earlier polar expeditions, Weyprecht proposed a drastic change in direction in polar investigations. He felt that the era of uncoordinated, independent expeditions aimed primarily at geographical exploration, but with negligible scientific results, was over. Useful scientific results could be attained only through a series of synchronous expeditions distributed over the polar regions to obtain one year's observations made according to a standard method. He envisaged the major effort being directed to meteorology, terrestrial magnetism, and auroral studies.

The outcome was the formation of an International Polar Commission, which first met in Hamburg on October 1, 1879. After several meetings of this commission, Weyprecht's dream became a reality as the First International Polar Year of 1882–1883. A total of eleven nations participated (United States, British Empire, France, Germany, Austrian Empire, Netherlands, Norway, Sweden, Denmark, Finland, and Russia). They established fourteen primary scientific stations, twelve of them in a circumpolar ring in the Arctic, and two in the Southern Hemisphere. The latter were the German station at Royal Bay, South Georgia, and the French station at Bahia Orange, not far from Cape Horn.

The meteorological observations to be taken at all stations included measurements of atmospheric pressure and temperature, relative humidity, wind speed and direction, cloud amount and type, precipitation, and hours of sunshine. The magnetic program was very demanding in terms of frequency of observations. Thus on so-called term days (the first and fifteenth of every month), the magnetic variation instruments were read every 5 minutes for 23 hours, and every 20 seconds for the final hour of the day.

The personnel of the German station at Royal Bay totaled ten men: six scientists led by Dr. K. Schrader, and four workmen. They traveled from Hamburg to Montevideo on board the steamer *Rio,* and from there on board the corvette SMS *Moltke* of the German Navy. They reached Royal Bay on August 20, 1882. The station buildings included a living hut, a magnetic and meteorological observatory, a barn, a zoological laboratory, and an observatory for watching the transit of Venus. Even quite recently the iron framework of the revolving dome from the last building was one of the most conspicuous relics on the site.

The observations started on schedule on September 1. In their off-duty hours, the scientists pursued their own specialties. Dr. Karl von den Steinen, a medical officer and ornithologist, made a detailed study of the avifauna. Dr. H. Will concentrated on botany and geology. E. Mosthaff surveyed the area and produced some elegant maps.

Particularly during the autumn and spring, the off-duty scientists made numerous trips by boat or on foot around the surrounding area. The Brocken, Krokisius, and Pirnerberg were climbed several times, and both the Ross and Weddell glaciers were visited. Measurements were made of the surface velocity of the Ross Glacier by taking repeated bearings on identifiable target boulders.

The Transit of Venus was observed on December 6, 1882. The sky was clear at the time and a perfect series of readings was obtained, despite violent winds that threatened to blow the revolving dome from the observatory. Late in August 1883, both the barograph and tide gauge traces showed unusual fluctuations. It was later deduced that these were caused by the eruption of Krakatoa in Sunda Strait on August 27. The German Navy's corvette *Marie,* Captain Krokisius, evacuated the party on September 6, reaching Montevideo on the 22nd.

Organization of the French contribution was entrusted to the French Navy, and the Cape Horn area was selected as its field of operations. The station personnel consisted of six scientists (five of whom were naval officers) and a support staff of fifteen. Leader of the shore party was Lieutenant-de-vaisseau Edmond-Jena-Léopold Courcelle-Seneuil. The ship's captain (and overall head of the expedition) was Capitaine-de-frégate Louis-Ferdinand Martial. His vessel was the bark-rigged steamer *Romanche.* She was to remain in the Cape Horn area for the entire year, engaged in oceanographic and survey work. *Romanche* sailed from Cherbourg on July 17, 1882. Having called at Teneriffe and Montevideo, it reached its destination, Bahia Orange, on the east side of Isla Hoste, just north of False Cape Horn on September 6.

Despite days of continuous rain, and some vicious williwaws (localized squalls), the observatories were completed and the observations began on September 26. All the buildings, including the living huts, had been completed by October 22.

On October 28 Marial took *Romanche* to sea on the first of a series of survey voyages that extended from Isla de las Estados on the east to Canal Cockburn and Punta Arenas on the west. Martial focussed especially on the area south of the Canal Beagle, and produced a superb chart of the area from there south to Cape Horn. *Romanche* called several times at the Anglican mission station at Ushuaia run by the Reverend Thomas Bridges. *Romanche* also spent 10 days at Port Stanley in the Falkland Islands in March.

Despite violent storms that tipped over one of the buildings and tore parts of the roofs off others, the scientific programs at Bahia Orange proceeded smoothly. Just as with the German station on South Georgia, the French scientists took advantage of a clear "window" on December 6, 1882, to get excellent observations of the transit of Venus.

All observations were discontinued on September 1, 1883, and the scientists with all their baggage had been reembarked by the evening of the 2nd. Having called at Ushuaia, *Romanche* headed for Punta Arenas and Cherbourg. Apart from the central studies of meteorology and terrestrial magnetism, the nine volumes of the official reports of the French expedition include detailed studies of the zoology, botany, and anthropology of the Cape Horn area.

As forerunners of the long list of complex multidisciplinary expeditions that would follow, both expeditions can rightly claim a very significant role in the scientific study of the Antarctic and adjacent areas. While no stations were established in the Southern Hemisphere as part of the Second International Polar Year (1932–1933), the major Antarctic effort involving numerous countries during the International Geophysical Year (1957–1958) represented a direct continuation of the work of the First International Polar Year. Plans are currently proceeding for celebrations and scientific efforts for another Polar Year in 2007–2008.

William Barr

See also **International Geophysical Year; South Georgia**

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INTERNATIONAL WHALING COMMISSION (IWC)

The International Whaling Commission (IWC) is the intergovernmental body established to conserve whale stocks and regulate whaling. There were sixty-six member nations in 2005.

Historical Background

The invention of the explosive harpoon combined with the development of steam-powered catcher boats in the 1860s heralded modern commercial whaling. The Antarctic quickly became the dominant whaling area. The first whaling station was established on South Georgia in 1904 when it took 195 whales. By 1930–1931, over 37,000 whales had been killed. The catastrophic decline in the price of whale oil led to the first effective limitation of catches (negotiated by whaling companies) in the early 1930s.

In the light of a world shortage of fats after World War II and earlier attempts to develop international agreements, discussions were held in London in 1945 and in Washington in 1946 on the international regulation of whaling.

Establishment of the International Whaling Commission

The International Convention for the Regulation of Whaling was signed in 1946 and established the IWC. Its objective is "to provide for the proper conservation of whale stocks and thus make possible the orderly development of the whaling industry," thereby placing conservation as well as exploitation at its forefront. Finding the difficult balance between "conservation" and the "interests of...the whaling industry" has dominated the history of the IWC.

The IWC comprises one commissioner from each government who has "one vote and may be accompanied by one or more experts and advisers." Regulatory measures (catch limits, seasons, size limits, etc.) can be amended by a three-quarters majority of members voting (excluding abstentions).

The convention states that amendments to the regulations "shall be based on scientific findings." The IWC has a Scientific Committee comprising scientists nominated by governments and latterly, a large number of invited experts.

Two aspects of the convention have attracted particular criticism: (1) governments can "object" to any decision with which they do not agree within a certain time frame; and (2) governments can issue permits to catch whales for scientific purposes. However, without these, the convention would probably not have been signed. Perhaps more significant in terms of good management is that operations cannot be restricted by numbers or nationality—this would have reduced economic and conservation problems associated with increasing numbers of vessels chasing limited quotas.

Up to the Moratorium

A serious problem of early management was the use of the Blue Whale Unit (BWU) to set catch limits (one blue whale equalled 2 fin, 2.5 humpback, or 6 sei whales). Unfortunately, this allowed whalers to reach their quota with a take consisting of multiple species of whales, allowing them to continue the industry at a time when being forced to take a single species would have proved economically unviable. This is apparent from the catch data up to the 1970s, which reveal that as blue whale catches declined, so fin whale catches (the next largest species) increased until they too were overexploited and sei whale catching began.

Although as early as 1952 it was recognised that the Antarctic catch quota was too high, it was difficult to get all whaling nations to agree to a reduction. This was the start of an unhappy period for the IWC. After considerable argument and controversy, by 1971–1972, the international catch limit had been reduced to 2300 BWUs and certain species, including the blue and humpback whales, had been completely protected from commercial whaling.

In the mid-1970s, largely as a result of the 1972 UN Conference on the Human Environment, the IWC established a permanent Secretariat, a decade of research, an international observer scheme, and a new scientific management procedure aimed at bringing all stocks to an optimum sustainable level and protecting stocks <54% of their estimated preexploitation size. Even so, doubts were expressed by some over (1) the theoretical and practical application of the management procedure and (2) the morality of whaling, irrespective of the status of the stocks.

There was also an increase in IWC membership—from eighteen (four nonwhaling) in 1963 to thirty-nine (twenty-six nonwhaling) in 1982 when, by a single vote, a moratorium on commercial whaling was adopted (effective 1986). Four nations (Japan, Norway, Peru and USSR) lodged objections, although Peru, and Japan subsequently withdrew theirs. In 2005, only Norway carries out commercial whaling.

It could be argued that the IWC's record up to 1982 was disastrous (e.g., in the Antarctic):

1. Blue whales had been reduced to at best 5% of their original numbers—hardly a good example of "conservation of whale resources"; and
2. The 1983–1984 catch (comprising only Antarctic minke whales which had not been considered worth catching in 1947–1948) had decreased to only 1/25th of the catch from when the IWC was founded—hardly "the orderly development of the whaling industry."

However, while it is easy with hindsight to condemn, no species became extinct due to modern whaling—IWC actions, while insufficient, were much better than nothing. Since the 1970s, the trend has been towards conservative management to a degree unparalleled in any fisheries commission. It is indicative of the inherent problems within the IWC that the moratorium decision is hailed by some as its greatest success and others as its most abject failure.

The Commission Today

Commercial Whaling

The Scientific Committee has developed a groundbreaking, extremely conservative procedure for determining safe catch limits (the "Revised Management Procedure"), which was adopted by the IWC in 1994. However, the IWC will not set catch limits for commercial whaling until it has agreed and adopted the "Revised Management Scheme" (RMS) that will include nonscientific issues (e.g., inspection and enforcement).

Aboriginal Subsistence Whaling

Limited aboriginal subsistence whaling is permitted for Denmark (Greenland, fin and minke whales), the Russian Federation (Siberia, gray and bowhead whales), St. Vincent and the Grenadines (Bequia, humpback whales) and the United States (Alaska, bowhead and gray whales).

Scientific Permit Whaling

Scientific permits have become a major controversial issue within the IWC with some claiming they are merely a way around the moratorium and others claiming that they are essential for rational ecosystem management. Proposed permits have to be submitted for review by the Scientific Committee but the ultimate decision lies with the proposing nation. In recent years the commission has voted to urge governments not to issue permits. The largest permits are issued by Japan. In the Antarctic, Japan has just completed a 16-year programme during which around 440 Antarctic minke whales were caught annually. Japan has decided to begin a new expanded Antarctic programme from 2005–2006 with annual catches of 850 Antarctic minke, fifty humpback (not to begin for 2 years) and fifty fin (ten in the first 2 years) whales.

Sanctuaries

IWC Sanctuaries can include no other measures than banning commercial whaling. The first sanctuary was south of 40° S between longitudes 70° W and 160° W

Members of the IWC, October 2005

Contracting Government	Adherence*	Status†
Antigua & Barbuda	21/07/82	
Argentina	18/05/60	Ex commercial whaling
Australia‡	10/11/48	Ex commercial whaling
Austria	20/05/94	
Belgium	15/07/04	
Belize	17/06/03	
Benin	26/04/02	
Brazil	04/01/74	
Cameroon	14/06/05	
Chile	06/07/79	Ex commercial whaling
People's Republic of China	24/09/80	Ex commercial whaling
Costa Rica	24/07/81	
Côte d'Ivoire	08/07/04	
Czech Republic	26/01/05	
Denmark	23/05/50	Ex commercial whaling; current aboriginal subsistence
Dominica	18/06/92	
Finland	23/02/83	
France‡	03/12/48	Ex commercial whaling
Gabon	08/05/02	
The Gambia	17/05/05	
Germany	02/07/82	Ex commercial whaling
Grenada	07/04/93	
Guinea	21/06/00	
Hungary	01/05/04	
Iceland	10/10/02	Ex commercial whaling; current scientific permit
India	09/03/81	
Ireland	02/01/85	
Italy	06/02/98	
Japan	21/04/51	Ex commercial whaling; current scientific permit
Kenya	02/12/81	
Kiribati	28/12/04	
Luxembourg	10/06/05	
Republic of Korea	29/12/78	Ex commercial whaling
Mali	17/08/04	
Mauritania	23/12/03	
Mexico	30/06/49	
Monaco	15/03/82	
Mongolia	16/05/02	
Morocco	12/02/01	
Nauru	15/06/05	
Netherlands	14/06/77	Ex commercial whaling
New Zealand	15/06/76	Ex commercial whaling
Nicaragua	05/06/03	
Norway‡	03/03/48	Current commercial whaling
Oman	15/07/80	
Republic of Palau	08/05/02	
Panama	12/06/01	Ex commercial whaling
Peru	18/06/79	Ex commercial whaling
Portugal	14/05/02	Ex commercial whaling
Russian Federation‡ (ex USSR)	10/11/48	Ex commercial whaling; current aboriginal subsistence
San Marino	16/04/02	
St Kitts and Nevis	24/06/92	
St Lucia	29/06/81	

*Some nations have left and subsequently rejoined. The date of entry applies to their most recent adherence.
†Commercial whaling refers to modern commercial whaling post-1900.
‡Initial members of the Commission (at its first meeting).

(Continued)

Members of the IWC, October 2005 (Continued)

Contracting Government	Adherence*	Status†
St Vincent & The Grenadines	22/07/81	Current aboriginal subsistence
Senegal	15/07/82	
Slovak Republic	22/03/05	
Solomon Islands	10/05/93	
South Africa‡	10/11/48	Ex commercial whaling
Spain	06/07/79	Ex commercial whaling
Suriname	15/07/04	
Sweden	15/06/79	
Switzerland	29/05/80	
Togo	15/06/05	
Tuvalu	30/06/04	
UK‡	10/11/48	Ex commercial whaling
USA‡	10/11/48	Ex commercial whaling; current aboriginal subsistence

*Some nations have left and subsequently rejoined. The date of entry applies to their most recent adherence.
†Commercial whaling refers to modern commercial whaling post-1900.
‡Initial members of the Commission (at its first meeting).

and lasted until 1955 when it was opened up to release pressure on other areas. At present there are two sanctuaries, the Indian Ocean Sanctuary (established in 1979) and the Southern Ocean Sanctuary (established in 1994).

Research

The IWC funds and acts as a catalyst for cetacean research (in 2004–2005 over $450,000 was allocated to scientific research in addition to work undertaken by individual governments). One major program is a series of Antarctic cruises to estimate abundance that has been carried out since 1978. The work carried out by the IWC Scientific Committee is recognized worldwide. The commission has increasingly published scientific reports and papers and this culminated in the launch of the *Journal of Cetacean Research and Management* in 1999.

The Future

The objective of the convention assumed that whales are a natural resource to be harvested but that this must be done sustainably. No population of whales is under threat of extinction from whaling and any acceptable management procedure will ensure that this cannot happen. However, there is clearly a divergence of opinion within the IWC on the acceptability of whaling, to an extent unparalleled in any similar organization. It is, for example, difficult to think of any fisheries organization where some of the members believe it is immoral to catch fish under any circumstances. This must be addressed if the IWC is not going to fragment, with potentially serious consequences for the world's cetaceans.

GREG P. DONOVAN

See also **Blue Whale; Fin Whale; Foyn, Sven; Humpback Whale; Larsen, Carl Anton; Minke Whale (Antarctic Minke Whale); Sei Whale; South Georgia; Southern Right Whale; Whales: Overview; Whaling, History of**

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INTRODUCED SPECIES

The Antarctic continent and some of the most southerly islands of the Southern Ocean have escaped the ravages of invasive species. The lower latitude islands have had their share of many of the invasive species that have ruined the ecology of oceanic islands throughout the world. The effects of these have in many cases all but eliminated the seabirds or changed the vegetation. A few species—mice, rats, cats, and rabbits—are the most prominent but there is a range of other species. Fortunately some failed to establish viable populations so their impact was either short lived or nonexistent. In recent years, considerable efforts have been taken to remove or control invasive species so that the impact can be reversed and the islands allowed to recover.

The southern islands fall into three geographical groupings; the Atlantic, the Indian, and the South Pacific Oceans. There are however some general aspects that affect all the islands. Where humans have had a permanent or long-term presence, the problem of invasive species is usually greater. The most widespread species, mice and rats, came in accidentally with early sealers and whalers, or as a result of shipwrecks. Rabbits and some others were deliberately liberated to provide a source of meat for shipwrecked mariners or semipermanent residents. Cats were introduced to reduce the rats and mice, as an ill-conceived early attempt at biological control, or have established from domestic pets turned loose.

Many of the islands share many of the southern seabird species, but several have their own endemic subspecies or even species. A good number have endemic terrestrial birds. Fortunately, few species have become extinct, as most islands are island groups, rather than a single land mass. Because some, often very small, islets have remained free of invasive species, the endemic species have been able to survive.

It is very obvious to the observer when visiting the islands as to whether an island does or does not host invasive species. In those that do, obvious endemics

Introduced Animals of Sub-Antarctic Islands in the Southern Pacific Ocean

	Mice	Rat	Cat	Rabbit	Sheep	Goat	Cattle	Other
Snares								
Auckland	✓		✓	E	D	E	E	Pig ✓
Campbell	✓	*norvegicus* E			E		E	
Bounty								
Antipodes	✓							
Macquarie	✓	*rattus* ✓	E	✓	E	E	F	Pig D, Horse D, Donkey D, Dog D, Weka E.

✓: Still present, D: Destroyed when no longer required by station or remain only as domestic, E: Eradicated directly, F: Failed to establish viable population (many were associated with early farming attempts or during establishment of metrological or research stations).
Note: Mammal animals referred to are wild or feral.

Introduced Animals of Sub-Antarctic Islands in the Indian Ocean

	Mice	Rat	Cat	Rabbit	Sheep	Goat	Cattle	Pig	Salmonid	Other
Amsterdam	✓	*norvegicus*	✓		D	D	✓	D		
St. Paul	✓	*rattus* E	F	E		F/E		F		
Crozet	✓	*rattus* ✓	✓	✓		F		E	✓ 2 sp	
Kerguelen	✓	*rattus* ✓		✓	✓				✓ 4 sp	Mallard✓, Mouflou✓, Reindeer✓.*
Marion	✓		E							
Prince Edward										
Heard		†			‡					§
MacDonald										

✓: Still present, D: Destroyed when no longer required by station or remain only as domestic, E: Eradicated directly, F: Failed to establish viable population (many were associated with early farming attempts or during establishment of metrological or research stations).
Note: Mammal animals referred to are wild or feral.
*Mink D, dogs D, cattle D, and mules D were all kept at the station.
†One record of a rat was observed on the beach at Atlas Cove during unloading operations in 1947.
‡Sheep were present on Heard in 1952.
§Dogs were present on Heard Island until 1954.

Introduced Animals of Sub-Antarctic Islands in the South Atlantic

	Mice	Rat	Cat	Rabbit	Patagonian Fox	Hare	Reindeer	Pig	Horse	Other
Tristan da Cunha		*rattus* ✓	✓					✓		Sheep D Goats D Dog D Donkey ✓ Cattle D
Gough	✓									
Falkland Islands	✓	*norvegicus* ✓ *rattus* ✓	✓	✓	✓	✓	D	✓	✓	Sheep D Cattle D Goats F Mink F Hare ✓ Dog D House sparrow✓ Mallard ✓ Brown trout ✓
South Georgia	✓	*norvegicus* ✓ *rattus* F					✓			Upland geese ✓
South Orkney Islands										
South Shetland Islands										
South Sandwich Islands										
Bouvetøya										

✓: Still present, D: Destroyed when no longer required by station or remain only as domestic, E: Eradicated directly, F: Failed to establish viable population (many were associated with early farming attempts or during establishment of metrological or research stations).
Note: Mammal animals referred to are wild or feral.

are missing and seabird numbers are minimal. There has been little work to quantify the decrease in seabird populations due to invasive mammals, but the decrease in seabird numbers or the absence of one or more species, can be attributed to the invasive species. On Marion Island, feral cats were estimated to have killed 250,000–500,000 small petrels annually. On some other islands there have been major reductions (e.g., Amsterdam albatross *(Diomedea amsterdamensis)* on Île Amsterdam and MacGillivray's prion *(Pachyptila macgillivrayi)* on Île St. Paul).

The terrestrial species have been affected more, and there have been some extinctions: the merganser *(Mergus australis)* in the Auckland Islands (although collecting also contributed to the extinction); the parakeet *(Cyanoramphus novaezelandiae erythrotis)* and rail *(Rallus philipensis macquariensis)* on Macquarie Island—again, some species have managed to survive on offshore islets; tussock bird *(Cinclodes antarcticus)* and Cobb's wren *(Troglodytes aedon cobbi)* on the Falkland Islands; the teal *(Anas aucklandica nesiotis)*, pipit *(Anthus novaeseelandiae aucklandus)* and snipe (*Coenocorypha aucklandica* subsp. nov.) on Campbell islands; the snipe *(C. a. aucklandica)* and teal *(A. a. aucklandica)* in the Auckland islands.

While introduced mammals command most attention, a few bird and freshwater fish have also been introduced. There have been introductions of plants, mostly accidental, with seeds being carried ashore in clothing or stock food. The grass *Poa annua* is the most widely distributed example. Some of the more permanently occupied islands have a greater range of alien plant species recorded. Information on invertebrates is harder to access but it parallels the introduced plant species.

The Falkland Islands were the only sub-Antarctic islands with an endemic mammal, the Falkland fox *(Dusicyon australis)*, which was exterminated by the early settlers. This was later replaced by the introduction of the Patagonian fox *(D. griseus)*, and efforts are now underway to control or eliminate this introduced species.

It is easy to look back and criticize our forebears, but what are we doing to overcome the problem and to prevent reoccurrences? Prevention is always cheaper than cure, and to prevent further species reaching the sub-Antarctic islands, the sovereign countries need to develop biosecurity policies and insist on strict quarantine procedures. Transport to southern islands has become easier and many are now on the annual tourist itinerary. To reduce the chances of new invasive species reaching the islands, landings should be permitted only at designated places. This would enable the most valuable biological islands to be excluded from visits by tourists. Even scientific research parties should be strictly regulated and the Republic of South Africa's rigid policy in relation to Prince Edward Island may serve as an example.

Even at designated landing sites, the tourist operators should be forced to insist on very strict procedures to prevent the introduction of animals and plants. Washing and sterilizing boots and checking clothing for seeds should be the minimum requirements. Hopefully, those visiting such places will appreciate their irreplaceable values and will have no problem with such enforced requirements.

Most countries with territory in the Southern Ocean have begun some projects to clear some of the invasive species from these islands. Notable ones have been Marion Island where feral cats have been removed, which stopped the high mortality of small petrels; St. Paul Island where the rats and rabbits were removed, and even before the last animals had been destroyed, MacGillivray's prion and great winged petrel *(Pterodroma macroptera)* had recolonized from a nearby rock stack, La Quille. At Macquarie Island, the Stewart Island weka *(Gallirallus australis scotti)* and cats were removed, and rabbits substantially reduced. Grey petrels *(Procellaria cinerea)* have since recolonized and populations of some of the smaller petrels have increased.

At Campbell Island, feral cats had died out some years after the removal of feral sheep (which were remnants of the farming era). Recently rats were removed in a major programme. Already the pipit has recolonized, and it is hoped to reintroduce teal from captive-reared stock. It is expected that petrels will begin to recolonize. On nearby Auckland Island, feral cattle, goats, and rabbits have been removed, and mice from one of the islands. Plans are being made to remove feral pigs from the main island.

Elsewhere, the French have controlled cattle numbers and their range on Île Amsterdam. On Îles Kerguelen some rat and rabbit eradication is underway on islands within the Golfe du Morbihan. This will give the seabirds that nest on some of the "clean" islands within the gulf the chance to expand onto these islands. In the Falkland Islands, some work has begun to remove rats and rabbits from some small islands, both there and on South Georgia. On the latter, it is important that rats are removed before the glaciers, which constrict their present range, recede, and allow them access to the remainder of the island. It is essential that efforts to correct the mistakes of the past are maintained or, even better, increased so that the sub-Antarctic islands can return to their full ecological potential.

Brian D. Bell

See also **Amsterdam Albatross; Amsterdam Island (Île Amsterdam); Auckland Islands; Campbell Islands; Gough Island; Heard Island and McDonald Islands; Kerguelen Islands (Îles Kerguelen); Macquarie Island; Prince Edward Islands; St. Paul Island (Île St. Paul)**

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IONOSPHERE

The global ionosphere is a result of the balance between the production and loss of ionization in the upper atmosphere; the exact form of these processes being complex and changing with season, solar cycle, altitude, and geographic position. Ionospheric constituents are constrained by the geomagnetic field, and altered by the neutral atmospheric composition and motions. The polar ionosphere is more complex because the Earth's magnetosphere is linked directly to it along near vertical geomagnetic field lines. The magnetosphere, energised by changes in the solar wind, imposes electric fields on the polar ionospheric plasma and ionizes deep into the Earth's atmosphere with high-energy particles. Finally, the Arctic and Antarctic ionospheres respond differently to these processes because of the greater separation of the geographic and geomagnetic poles in the Southern Hemisphere. But none of this was known when the Antarctic ionosphere was first exploited.

Almost two decades before the ionosphere was explored scientifically, Douglas Mawson's 1911–1914 Australasian Antarctic Expedition used Macquarie Island (54°30′ S, 158°57′ E) as a relay station for wireless communications (on 500 kHz) between Cape Denison (67°00′ S, 142°40′ E) on the Antarctic mainland and more northern locations. Considerable difficulty was initially experienced but after improving the equipment location, successful communications were achieved in February 1913. Mawson recognised the potential scientific value of propagation experiments for exploring the polar upper atmosphere, but his technicians could not mount any definitive experiments and the analysis of the communication records was delayed in publication so that Arctic propagation work overtook the results.

During the Byrd Antarctic Expedition (1929–1930) Malcolm Hanson made the first ionospheric observations for either polar region using a Breit and Tuve pulse system—a forerunner of the modern ionosonde. Working in heroic conditions, at Little America (78°34′ S, 163°56′ W), Hansen built up a seasonal picture of the ionosphere. His most outstanding finding was the discovery that the upper ionospheric layers persisted through the polar night, while the lower layers disappeared. No successful explanation for this observation was found for over 40 years. He also showed the layers had a diurnal variation in height and that returns could be complex and apparently come from large ranges. Although his results received coverage at conferences and in print, they were then neglected.

After these notable firsts, little additional progress was made monitoring and understanding the Antarctic ionosphere until the International Geophysical Year (IGY), which proved to be a watershed in many fields of geophysical science.

The vertical-incidence ionosonde is a major tool for studying the Antarctic ionosphere. An ionosonde is a cosited swept-frequency pulsed transmitter and receiver forming a vertically directed high-frequency (HF) radar system. A frequency pulse is transmitted upwards and may be reflected from the ionosphere, the reflected signal being observed with the receiver. This process is repeated at a sequence of frequencies usually starting at 1.0 MHz and finishing around 20 MHz. A picture of the ionization observed above the ionosonde is then built up into an ionogram, which is constructed by displaying the returned signal as a function of frequency (typically, the horizontal axis) and time delay, usually called virtual height (the vertical axis).

Ionosonde stations were established on some sub-Antarctic islands by 1946 and the first mainland observations were made in 1950 at Terre Adelie (60°40′ S, 140°1′ E). At this time, it was felt that there was little difference between the two polar ionospheres. However, the IGY gave a major impetus to the geophysical sciences and many countries opened ionosonde stations in Antarctica in 1957–1958. Among other results, the IGY observations showed that in the Weddell Sea sector, during summer, the peak electron density was high during local night with lower values during the daytime. In winter, this was reversed and typical midlatitude behaviour was seen. Also, across the polar cap the peak height and electron density in the polar cap of the ionosphere was found to be a function of Universal Time (UT), rather than local time, having a maximum near 06 UT. This is unique to the Antarctic ionosphere and no similar feature has been unambiguously identified in the Arctic. These and similar results helped define the unexpected differences between the Antarctic and Arctic ionospheres and initiated a search for their explanation.

The Earth's atmospheric density decreases exponentially with height by several orders of magnitude between the ground and the ionosphere. The lowest atmospheric layer is the troposphere; home of the "weather" and all life on Earth, where chemical composition is largely constant with height and temperature decreases gradually upwards. This region is bounded by the tropopause (10–12 km), and above this is the stratosphere, a region of increasing temperature that maximises near the stratopause (50 km), where ozone absorbs the Sun's ultraviolet radiation. The temperature falls in the mesosphere, reaching a minimum of 180 K at the mesopause (80–85 km); the coldest region of the Earth's atmosphere. Above this, solar radiation is absorbed, heating the thermosphere to over 1000 K. Below the turbopause ($\sim$120 km) the atmosphere is mixed uniformly and above it mixing is inhibited and the various atmospheric species separate under molecular diffusion. The bulk of the ionosphere is embedded in the thermosphere. Modelling suggests changes in the tropospheric climate, possibly due to anthropogenic sources, may be more easily detected in the upper atmosphere, and especially in the Antarctic ionosphere. Preliminary studies support this conjecture, making this an important, current research topic.

Monochromatic radiation absorbed in an atmosphere where the density decreases exponentially upwards will, at some height depending on the absorption process, have a maximum ion-electron production rate. Provided the loss rates are fast enough, the number density of free electrons will follow the shape of the production function, having a maximum where production is greatest. This is called a Chapman layer. While misleading in some respects, the concept of an ionospheric layer has proved valuable for organising thinking about the nature of the global ionosphere. Conventionally, the ionosphere is divided into three layers, the D layer (below 90 km), E layer (peaking near 110 km), and F layer (200–500 km), the latter being further divided into the F1 layer (200–250 km) and F2 layer. All the layer properties depend on time of day, season, solar cycle, and geographic location.

The normal E region is formed by the absorption of extreme-ultraviolet (EUV) radiation and has a peak near 110 km, the free electrons being lost rapidly in fast chemical reactions. Because of the fast loss rate, the amount of ionization present in the E region can be described by the solar zenith angle (which depends on the Sun's position in the sky and the geographic location). The normal E region forms rapidly at dawn as the Sun appears, reaches a maximum at local noon as the Sun reaches its zenith position in the sky, and disappears at dusk when the Sun disappears. Similarly, during a solar eclipse, the extent of ionization in the E region closely follows the epoch of the eclipse. No other ionospheric layer is as well behaved.

Above the E region, charged particle motion is affected by the geomagnetic field. Charged particles in free space gyrate in circles about the magnetic-field lines. The time for one circuit of a field line, and the radius of gyration, both depend on the particle mass; consequently, electrons travel more rapidly in smaller gyrations than the heavier ions. As the altitude increases and the distance between collisions increases, the geomagnetic field influence also increases. Low in the E region the geomagnetic field has little effect on either ions or electrons, but by 100 km the smaller gyrations of the electrons allow them to follow the geomagnetic field between collisions and by 140 km both ions and electrons are constrained by the geomagnetic field.

The F region is the most important and most complex ionospheric layer. Fast chemical reactions in the E region (mainly ion-ion recombination) lead to charge neutrality. However, the decrease in atmospheric density means fewer suitable ions are available and different, slower chemical reactions (including attachment reactions between electrons and neutral species) predominate in the lower F region, leading to the formation of the F1 layer during day time. In fact, the chemical loss rate falls off more rapidly than the production rate as transport effects become important. In the upper F region, downward diffusion of particles under the action of gravity and constrained by the geomagnetic field (called ambipolar diffusion) is the primary loss mechanism and, to a first approximation, the F-region ionization peak is in diffusive equilibrium. But this alone does not explain its climatology and persistence throughout the night.

Thermal heating of the neutral atmosphere during daytime and cooling at night leads to a pressure gradient forming across the geographic poles from the late afternoon to the early morning. The thermospheric wind results from the balance between the pressure gradient, viscosity, Coriolis force, and collisions with the ions, which are constrained by the geomagnetic field. Viscosity and collisions are dominant in the F region resulting in the wind blowing across the pole in the direction of the pressure gradient. The separation between the geographic and geomagnetic poles is sufficient for winds to explain the Weddell Sea anomaly. During daytime summer the prevailing thermospheric wind blows across the South Geographic Pole, carrying the ionosphere down the field lines into a region of faster loss rate, resulting in reduced ionization. Twelve hours later the region is still illuminated by the Sun and the same wind pushes ionization up field lines into a region of lowered loss rate leading to increased ionization. In winter, with no solar illumination present the wind cannot increase nighttime ionization above the daytime level.

The Antarctic ionosphere UT variation mentioned earlier also depends on wind action and the separation of the geographic and geomagnetic poles. At 06 UT, the geographic pole is on the midnight side of the magnetic pole, so the neutral wind blows over the polar cap, away from the Sun moving ions up the field lines, into a region of lower loss rate, increasing both the peak electron density and peak height. In the Northern Hemisphere the smaller separation between the poles results in little or no UT effect. These uniquely Southern Hemisphere relationships are complex, the balance between the different effects depending on season and solar cycle.

A distinguishing feature of the polar ionosphere is the presence of high-energy charged particles (usually electrons) that precipitate (travel) down geomagnetic field lines and ionize the neutral atmosphere. The higher the energy of the incoming particles, the deeper they penetrate into the atmosphere; the height of maximum production depending on the incoming particle energy and the production rate depending on the particle flux. These charged particles either come directly from the Sun, or gain their energy from processes in the magnetosphere that are driven by the Sun.

The Sun's atmosphere, called the solar wind, is a turbulent, supersonic plasma (containing electrons, ions and a magnetic field) flowing outwards from the Sun, past the Earth, and out beyond the orbit of Pluto. Threaded throughout the solar wind is a magnetic field, called the interplanetary magnetic field (IMF), which is frozen into the plasma; that is, the structure of the IMF is dominated by plasma motions. Periodically, the solar wind is disrupted by massive disturbances called coronal mass ejections (CME), which start at the solar surface as eruptions of solar material and form complex plasma disturbances by the time they sweep past the Earth's orbit. When the turbulent outflow of the CME strikes the Earth, the impact on the magnetosphere can be experienced at ground level due to a series of processes whose study forms part of the growing field of space weather.

The Earth's geomagnetic field carves out a comet-like cavity in the turbulent solar plasma, and the outer boundary is the limit of the Earth's influence. The cavity is compressed in the sunward direction, the dayside of the Earth, and stretches away from the Sun in a long tail on the Earth's night side. The outer boundary contains the magnetosheath and magnetopause, and the magnetosphere fills the interior of the cavity above the ionosphere. The geomagnetic field lines that make up the bulk of the magnetosphere pass through the polar ionosphere as they connect to the Earth, so the polar ionosphere is directly linked to the magnetosphere. The outer magnetosphere faces towards the Sun and changes in Universal Time in response to solar-wind disturbances, while the Earth, the plasmasphere and the neutral atmosphere rotate inside this cavity dragging the embedded polar ionosphere through a changing magnetospheric environment. The larger offset of the poles in the Southern Hemisphere leads to differences between the two polar ionospheres.

As the turbulent solar wind flows past the Earth, charged particles within the magnetosphere are accelerated by varying amounts depending on their location in the magnetosphere. Dynamic events, such as magnetic storms (initiated by solar wind disturbances), and substorms (events that appear to be contained entirely within the magnetosphere, although probably triggered by changes in the IMF) modify the magnetospheric acceleration processes. The precipitating particles accelerated in different magnetospheric regions precipitate down the geomagnetic field lines imposing gross order on the polar ionosphere. While one-to-one identification between magnetospheric regions and ionospheric features is a little subjective, the prospect offers tantalizing research possibilities.

During a magnetic storm all high-latitude processes increase in complexity as the magnetosphere deposits energy and momentum into the polar thermosphere. Precipitating electrons and protons collide with the atmosphere and deposit five to ten times more heat directly into the neutral atmosphere. The polar ionosphere will be modified in highly complex ways by the precipitating particles associated with the storm, possibly solar protons that have ionized deep into the polar ionosphere, and by increased magnetospheric convection and enhanced thermospheric winds. The particle ionization increases the thermospheric conductivity and combined with the magnetospheric convection electric field produces the main atmospheric energy source during the storm. The resulting Joule heating effect can be two or three times greater than precipitation effects alone. Furthermore, the regions responsible for magnetospheric energy sources, as well as increasing the amount of energy deposited into the neutral atmosphere, expand equatorward by as much as 10° to 15°, extending the domain of the polar ionosphere to midlatitudes. The energy increase disrupts the neutral atmosphere and ionosphere globally and is the source of an ionospheric storm; a global event that produces massive changes in the mid- and low-latitude ionosphere. The culmination of these processes is a rich domain for space weather research.

When precipitating particles ionize the D region, HF absorption increases. A riometer is a vertically directed, single-frequency (often 30 MHz) receiver that records the signal strength of incoming galactic emissions, changes being interpreted as absorption due to particle precipitation. Absorption events that prevent ionosondes from recording ionograms can be monitored by a riometer. There are two important types of absorption event. Some major solar flares produce energetic protons that are guided to high latitudes first by the IMF and then by the geomagnetic field. There they can ionize nearly the entire continental Antarctica D region leading to a sustained absorption event, called polar-cap absorption (PCA), which can last for several days. When a PCA is seen on a cosmic-ray detector at the ground it is called a ground-level event (GLE). Auroral absorption is almost entirely restricted to the auroral zone and is caused by particles accelerated in the magnetosphere. It shows much greater temporal structure (briefer, more intense events with diurnal variation in occurrence) and smaller spatial structure than a PCA. New multibeam riometers show these events can intensely ionize only a small patch of the sky.

Energetic electrons ionize the E region forming transient E-region layers, called sporadic E (Es) after their midlatitude counterparts that are produced by wind shears. However, like the normal E layer, and unlike the thin midlatitude Es layers, the particle layers are thick enough to prevent radio waves from passing through them. On ionograms, the particle-Es layer appearance alters depending on whether the layer is overhead (called particle E) or oblique (often called retardation Es) and whether it is accompanied by irregularities (called auroral Es). In principle, as an ionizing region moves towards and above an ionosonde station, the ionograms will first show retardation Es and auroral Es, which then change to particle E when overhead. By recognizing the overhead particle-E layer, it is possible to estimate the likely incoming particle energies by measuring the layer height. However, this is often difficult because any change in the ionizing particles will produce immediate changes in the E-region ionization due to the fast chemical loss processes. Less energetic electrons can ionize the F region leading to increased ionization irregularities that appear on ionograms as spread F.

In the polar ionosphere, the magnetospheric convection electric field maps down geomagnetic field lines into the ionosphere causing it to move in a direction perpendicular to both the convection electric field and the geomagnetic field. The neutral atmosphere collides with ions drifting in response to this field and gains momentum, adding the magnetospheric convection electric-field pattern to the polar neutral wind field. Modern ionosondes making Doppler measurements can detect the convection effects in the ionosphere, as can the more powerful coherent HF radars that are organised in a cooperative network (called SuperDARN, for Super Dual Auroral Radar Network) covering both polar regions; SuperDARN offers especially rich research prospects.

The auroral region forms a defining boundary for the polar ionosphere and it is tempting to organise all polar phenomena with respect to it. Auroral phenomena are associated with the precipitation of energetic electrons into the atmosphere. Optical aurora, a by-product of the ionization and subsequent chemical-loss processes, are linked to Es on ionograms. Auroral precipitation can be divided into two regions, an inner region corresponding to the oval and associated with soft electron fluxes forming Es layers and spread F on ionograms, and a second zone 5° to 10° equatorward of the oval associated with more energetic electrons, diffuse aurora and greater HF absorption. Like all polar phenomena, these vary constantly.

Equatorward of the auroral oval, the F-region ionization reduces, forming a trough where ionization levels are lower than those seen in either the auroral or midlatitude ionosphere. The trough is thought to be formed by a combination of electron-loss processes and convection circulation, some convection paths lying in regions of low production for several hours. At the equatorward edge of the auroral oval the trough ionization increases sharply due to increased particle precipitation, although other processes may be present and even dominant at times. A further complication is that more than one trough is seen, both in space and in plasma constituents. There are fewer synoptic studies of the Southern Hemisphere trough, but what evidence there is indicates differences from the Northern Hemisphere. The southern trough is seen in all seasons and not just winter and equinox, and all times of the day rather than only at night.

The cusp region centred on local noon and poleward of the auroral oval is open to magnetosheath particles that can precipitate into the polar daytime ionosphere between the cusp and the auroral oval, heating the ionosphere and increasing irregularities. Patches of ionization can be detected as entities using airglow, incoherent-scatter radars (only available in the northern hemisphere), and ionosondes. When the IMF is southward, 200 to 1000 km diameter patches of roughly circular ionization enhancements, sometimes a factor of ten above the background ionization, move across the polar cap with the general plasma drift. Patches are likely to be caused by convection entrainment passing through the polar cusp and are associated with a tongue of F-region auroral-oval ionization that was first identified in IGY ionosonde data. When the IMF is northward, weaker more elongated features aligned with the noon-midnight line drift across the polar region from dawn to dusk.

The polar ionosphere is permeated by ionization irregularities of widely varying spatial and temporal form. Smaller-scale irregularities, from metres to tens of kilometres in size, cause scintillations on global transionospheric radio-propagation paths, and after the equatorial-anomaly region scintillations are most severe near the auroral zone. Scintillations show considerable fine structure and while particle precipitation is clearly involved, other processes including plasma instabilities contribute to the drifting, and temporally evolving irregularity composition. All aspects of polar irregularities are the subject of ongoing research efforts.

The polar ionosphere forms a highly complex interface between the neutral atmosphere and the magnetosphere, with energetic particles accelerated in the magnetosphere increasing its ionization and convection drifts modifying the polar thermospheric winds. In addition, because the Antarctic ionosphere is accessible from the ground, it offers a valuable ground-based observation platform for studying the magnetosphere, complementing the rich space-based data sources now available and anticipated in the future. Dynamic processes in the ionosphere (ionization, chemistry, diffusion, winds) depend on geographic location and geomagnetic dip whereas magnetospheric processes (particle precipitation, convection) depend on the position of the geomagnetic pole. The greater polar separation in the Southern Hemisphere offers possibilities for discriminating between competing magnetospheric and geographic processes in the ionosphere, further increasing the research value of the Antarctic ionosphere.

PHIL WILKINSON

See also **Antarctic: Definitions and Boundaries; Aurora; Auroral Substorm; Australasian Antarctic Expedition (1911–1914); Cosmic Rays; Geomagnetic Field; Geospace, Observing from Antarctica; International Geophysical Year; Macquarie Island; Magnetic Storm; Magnetosphere of Earth; Mawson, Douglas; Plasmasphere; Solar Wind; South Pole; United States (Byrd) Antarctic Expedition (1929–1930)**

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ISLANDS OF THE SCOTIA RIDGE, GEOLOGY OF

The Scotia Ridge is the name given to the eastward-closing cusp of submarine ridges and rugged islands that connect the Andean Cordillera of South America with the Antarctic Peninsula, partially enclosing the Scotia Sea. It includes the island of South Georgia, the South Sandwich Islands, and the South Orkney Islands and is composed partly of fragments of an original continental connection between South America and the Antarctic Peninsula and new crust generated by the subduction of oceanic crust belonging to the South American plate beneath the Scotia Sea. It forms a complex boundary of the Antarctic plate with the Pacific and South American plates and contains the small tectonic Scotia, Sandwich, and Drake plates. Only the East Scotia Sea is actively spreading. On the eastern side of the Scotia Sea, oceanic crust belonging to the South American plate is being subducted beneath the Scotia Sea to form the volcanic South Sandwich Islands as an intraoceanic island arc. The northern and southern parts of the Scotia Ridge are slow-moving sinistral transform faults accommodating relative movement between the larger plates. Both South Georgia and the South Orkney Islands were part of the Mesozoic margin of Antarctica and South America. Major magmatic arcs were established along the length of the southernmost Andes and Antarctic Peninsula during the late Mesozoic and Cenozoic initially during a period of widespread extension that lead to the development of the South Atlantic Ocean and Weddell Sea basins.

The Scotia Sea and Scotia Ridge developed their present form over the past 40 million years as a complication of the South American–Antarctic plate boundary representing the final stage in the breakup of the Gondwana supercontinent and the isolation of Antarctica in a South Pole position. Fragmentation of the land connection dispersed continental blocks eastwards to form the north and south Scotia Ridges.

South Georgia

It is generally accepted that South Georgia was first sighted by Antonio de la Roche in 1675 with the first geological survey carried out during the South Georgia Survey 1951–1957. The island is the emergent part of an isolated microcontinental block the geology of which can be matched closely to that of western Patagonia and Tierra del Fuego, the South Georgia block having formed part of the Pacific margin of

Gondwana. For much of the Mesozoic, the southwestern edge of Gondwana was an active plate margin above the easterly subducting, proto-Pacific ocean floor. The rocks of South Georgia represent various stages in the evolution of the active margin, in particular the development of an island-arc–back-arc-basin system of middle Jurassic to mid-Cretaceous age.

The oldest rocks are polyphase-deformed metasediments that were intruded by an extensive tholeiitic suite of gabbroic plutons which migmatized the country rock. This magmatic episode thinned the continental crust; further rifting and emplacement of tholeiitic magma led to the creation of mafic crust (composed of lavas, dykes, and plutons) with oceanic crustal characteristics. The middle–late Jurassic magmatic episode is represented by an igneous and metamorphic complex (Drygalski Fjord Complex) and an ophiolite suite, now exposed in the southern part of South Georgia (Larsen Harbour Complex). It is likely that a similar mixture of thinned continental crust and oceanic crust forms much of the hidden floor of the marginal basin

During the early Cretaceous an island-arc–back-arc-basin system was active in the area. The island-arc suite, a series of mudstones with interbedded tuffs and overlying volcaniclastic breccia, crops out on isolated islands off the southwest coast. All of the pyroclastic rocks are andesitic and have the calc-alkaline chemistry typical of island arcs. Deposition of the clastic rocks began in the latest Jurassic and continued into the late Aptian or Albian; intrusions of dioritic stocks, sills, and dykes of late Cretaceous age represent a late phase of igneous activity.

The age of deposition in the marginal basin is poorly constrained but probably contemporaneous with deposition of the arc sediments. Most of South Georgia is formed of a c. 6 km thick unit of Lower Cretaceous andesitic greywackes (Cumberland Bay Formation), derived from the volcanic arc and deposited by turbidity currents. These flowed both across and along the basin, forming a laterally variable complex which was penetratively deformed early in the late Cretaceous. Deformation was associated with closure of the basin and westerly underthrusting of the basin floor. The volcaniclastic turbidites were thrust over a series of siliciclastic turbidites (Sandebugten Formation) of unknown age that may have been derived from the opposite (continental) side of the basin.

The arc and the basin were separated by a major fault during deposition. The line of this is now marked by a mylonite zone that records both dip-slip and strike-slip movement. This is the only unit in the island younger than mid-Cretaceous.

South Sandwich Islands

The South Sandwich Islands were first sighted on January 31, 1775, by Able Seaman Freezland from Captain Cook's ship HMS *Resolution*. They form a 350 km long, north–south orientated, cresent-shaped volcanic arc that is regarded as one of the classic global examples of an intraoceanic arc. The eleven islands are small, typically 3–8 km across, and entirely volcanic in origin (Baker 1968, 1978). They typically rise 500–1000m above sea level and are subaerial summits of edifices that rise some 3 km above the surrounding seafloor. The arc is currently volcanically active with intense fumarolic activity on several of the islands, and there have been at least six historic eruptions. The only radiometric dates for the arc are four K-Ar ages on volcanic rocks, the oldest being 3.1 ± 0.3 Ma (Baker et al. 1977). The arc is tectonically simple, being located on the small Sandwich Plate, which is overriding the southernmost part of the South American Plate at the South Sandwich Trench. The arc lies on crust that formed at a back arc spreading centre that has been active for at least 15 million years. Extension may have been initiated as a result of a change of direction of South American–Antarctic relative motion about 20 Ma.

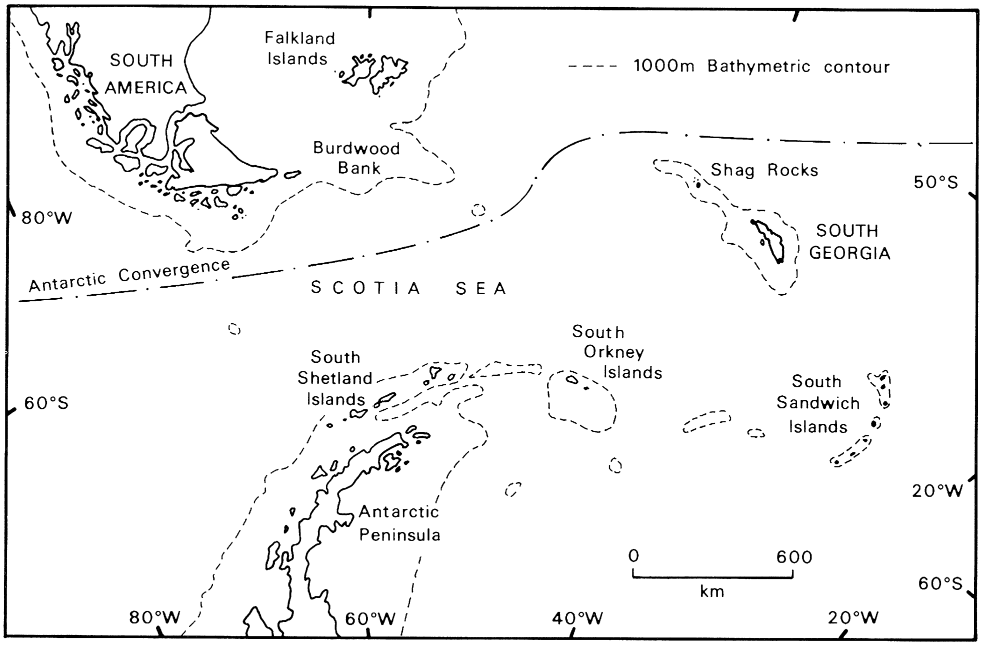
Compositionally the volcanic rocks range from basalt to rhyolite with mafic rocks (basalt and basaltic andesite) being volumetrically dominant. They show three geochemical trends, low K tholeiitic, tholeiitic, and calc-alkaline with high-Al basalts being common. The mafic magmas were derived from mantle that had been depleted by a previous melt extraction probably related to the back arc spreading.

South Orkney Islands

The South Orkney Islands are a group of mountainous islands lying northeast of the Antarctic Peninsula and on the southern part of the Scotia Ridge. They were discovered during a joint cruise by Capt. George Powell, a British sealer in the sloop *Dove,* and Capt. Nathaniel Palmer, an American sealer in the sloop *James Monroe* in 1821.

The islands consist of metamorphic (Scotia Metamorphic Complex) and sedimentary rocks (Greywacke Shale Formation) that represent the products of subduction-related accretion and of sedimentation, respectively, in a forearc environment along the Pacific margin of Antarctica before and subsequent to the fragmentation of Gondwana. The rocks lie on the Pacific side of any relics of the contemporaneous magmatic arc.

BAS GEOMAP :1 SOUTH GEORGIA

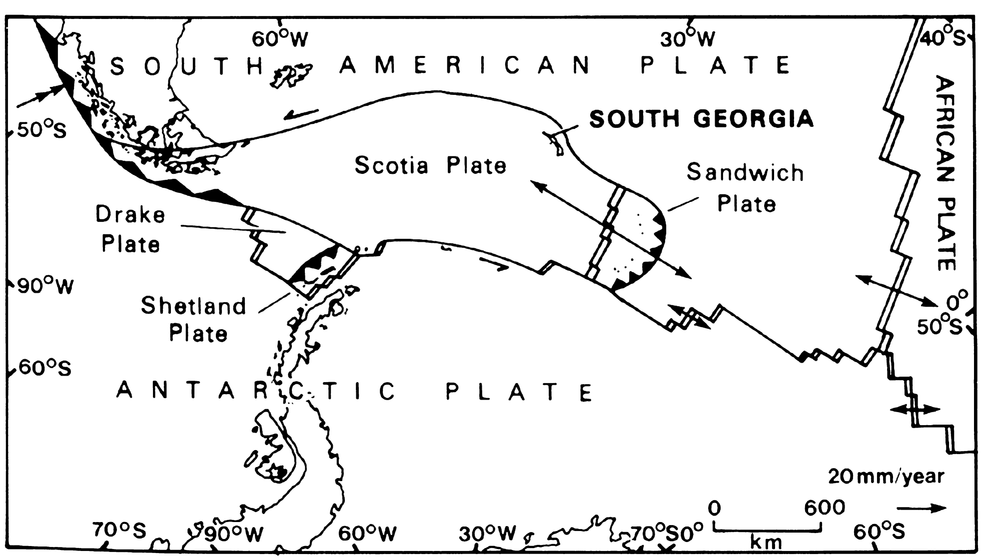


Location map showing the islands of the Scotia Ridge between South America and the Antarctic Peninsula.

The islands were rotated and translated from an original position within the Powell Basin during the formation of the Scotia Ridge.

Scotia Metamorphic Complex (SMC)

The SMC consists of interlayered graphitic phyllite, mica schist, metachert, marble, calc-silicate, and amphibolite. The metamorphic grade is commonly epidote amphibolite or amphibolite (Tanner et al. 1982). It has yielded K-Ar cooling ages of 190 Ma on hornblende and micas. The mica schists comprise mapable units of pelitic or semipelitic schist, psammite, and rare quartzite layers. The amphibolites include fine grained greenschist, coarse hornblende gneiss, epidote amphibolite, and calc amphibolite. Massive white marble bands up to 3 m thick are the most distinctive rocks. Whole rock chemical analysis suggests that the amphibolites are metamorphosed basaltic rocks and



Present-day plate tectonic map of the Scotia Ridge (after British Antarctic Survey, 1985).

have affinities with MORB-type and alkali basalt of an intraoceanic island tectonic setting. Finely laminated Mn rich garnetiferous quartzite layers are interpreted as meta cherts. The protoliths on Signy Island are typical of a subduction zone environment (ocean basalt, limestone, chert, clastic sediments). The intense and pervasive ductile shearing, tectonic interleaving of lithologies and coaxial folding has lead to suggestions that the deformation and accompanying metamorphism represented the subcretion of material from a downgoing oceanic plate beneath the forearc wedge at depths in excess of 20 km in the subduction zone (Dalziel 1984). A structural analysis has shown that the subduction complex rocks on have suffered intense shearing throughout their deformation history in a consistent north-northwest–south-southeast direction during ductile thrusting towards the NNW. Vertical or steeply dipping dolerite dykes intrude the metamorphic rocks.

Greywacke-Shale Formation (GSF)

The sedimentary strata consist of poorly fossiliferous greywacke and shale of turbiditic facies associated with rare mafic pillow lavas containing prehnite and pumpellyite. Bedding and primary structures are ubiquitously recognizable although the rocks are everywhere deformed by one major set of subisoclinal to tight asymmetric folds with associated axial planar slaty cleavage. The folds vary in attitude from upright through overturned and reclined to recumbent. The regional setting, structural style, and an observed transition structurally downward into the metamorphic rocks of the SMC suggest that the strata were deposited partly in trench-slope basins that are within the zone of active deformation in the wedge. Upper Triassic fossils were uncovered from a chert layer conformable within greywacke and shale layers off Laurie Island (Dalziel et al. 1981).

Spence Harbour Conglomerate/Powell Island Conglomerate

At the eastern end of Coronation Island, the metamorphic rocks are unconformably overlain by a sequence of conglomerates and sandstones referred to as the Spence Harbour Conglomerate and elsewhere within the island group as the Powell Island Conglomerate. The conglomerates consist almost entirely of metamorphic debris derived from the underlying metamorphic complex. A thick black shale bed contains a fauna of poorly preserved brachiopods, bivalves, and gastropods, belemnoidia together with some fragments of fossil wood and one or two echinoid spines and plant debris. The typical conglomerate is a well indurated light grey or buff coloured rock composed of closely packed pebble-sized lithic fragments embedded in a matrix of grit or coarse sand.

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See also **Fossils, Invertebrate; Fossils, Plant; Gondwana; Plate Tectonics; South Georgia; South Orkney Islands; South Shetland Islands; South Sandwich Islands; Volcanoes**

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ISOTOPES IN ICE

Like other elements, the constituents of water—oxygen and hydrogen—occur in different isotopes. Different isotopes of one element have different atomic masses due to a different number of neutrons in the nucleus. Stable oxygen atoms (which always have eight protons) have eight, nine, or ten neutrons, resulting in three isotopes with the atomic mass numbers 16, 17, and 18 respectively (^{16}O, ^{17}O and ^{18}O).

Hydrogen has two stable isotopes, ^1H and ^2H (deuterium, represented by symbols ^2H or D). The mixing ratios R of the isotopes in different natural substances on Earth are rather stable:

oxygen:	^{16}O	^{17}O	^{18}O
mixing ratio:	997,570 ppm	380 ppm	2,050 ppm
hydrogen:	^1H	^2H (Deuterium)	
mixing ratio:	999,885 ppm	115 ppm	

Isotopes of one element have the same chemical characteristics. Small fractionations in their composition occur in processes, depending on the atomic mass, like evaporation, condensation, and diffusion. Relative deviations of isotope ratios can be measured very precisely in special isotope ratio mass spectrometers and recently also by laser spectroscopy.

Because variations of isotopic ratios are small, they are expressed as so called δ-values defined as:

$$\delta = \left(\frac{R_{sample}}{R_{standard}} - 1\right) \cdot 1000(‰)$$

Mean ocean water is taken as standard for ^{18}O and ^2H (The absolute mixing ratios for the Vienna Standard Mean Ocean Water provided by the International Atomic Energy Agency (IAEA) are 155.76 ppm for ^2H and 2005.2 ppm for ^{18}O). Water with a ^{17}O molecule is seldom used for ice core analyses.

Water evaporating from the ocean is depleted in heavy isotopes because water molecules with a heavy isotope have a slightly lower vapor pressure than normal molecules. If clouds loose water by precipitation, heavier isotopes are preferred. Heavy isotopes in the clouds are, therefore, more and more depleted as more water is lost by precipitation. The remaining relative water content, compared to the one at the source region, depends on temperature. Therefore, the isotopic composition of precipitation depends on condensation temperature as well. This is the main principle on which the isotopic "paleothermometry" is based.

The main goals of the water isotope analyses of ice cores are

- To reconstruct continuous and detailed profiles of past local temperature changes by combined water isotope analyses.
- To obtain information about the origin of the water deposited on site as snow and about the associated hydrological cycle.
- To contribute in establishing accurate time-scales for ice cores by counting annual layers, if seasonal variations can be detected in the isotope profiles or by estimating past accumulation rates based on the local temperature.

The δ-values for oxygen and hydrogen in precipitation depend not only on condensation temperature but also on the temperature of the source regions and the cooling process of the air. In fact, δ-values of single precipitation samples are not well correlated with the local temperature during precipitation. On the other hand, it has been observed that the δ-values of precipitation samples collected during one year are well correlated with the mean annual surface temperature at the sampling sites, especially in polar regions. General circulation models allow us to calculate the pattern of mean δ-values as function of different climatic conditions (Jouzel et al. 2000).

Ice cores drilled in polar ice sheets provide precipitation samples from the past. δ-values of ^{18}O or ^2H measured on such samples allow us to estimate the local temperature in the past. The δ^2H-record of the Vostok ice core allows us to reconstruct the temperature evolution during the past 420,000 years (Petit et al. 1999). The data are available from Petit et al. (2001). The record shows that the temperatures were most of the time lower than today. The cold epochs, called ice ages, have been interrupted about every 100,000 years by warm epochs, so called interglacials. Our present epoch, the Holocene, lasting about 12,000 years until now, is the most recent of these interglacials. The difference in the δ^2H values between the last glacial maximum (lowest temperatures) and the Holocene is about 60‰; this corresponds, according to present knowledge, to a local temperature difference of about 9°C.

A more recent ice core drilling at Dome C in Antarctica allows us to extend the isotopic record to 740,000 years before present (BP) (EPICA community members 2004). One interesting result is that the interglacials before 450,000 years BP were less warm but lasted longer.

Either δ^2H or $\delta^{18}O$ can be indifferently used to reconstruct temperature records. The two values are correlated by the relation: $\delta^2H = 8 - \delta^{18}O + d$. The parameter d is called the deuterium excess. It would be constant if equilibrium processes alone took place during evaporation and condensation of water. However, ocean water often evaporates into air with humidity below the saturation pressure and nonequilibrium processes also occur during the formation of snow. The deuterium excess in polar precipitation is mainly influenced by the conditions in the oceanic moisture source region (temperature, relative humidity and to a lesser degree, wind speed). The deuterium excess, d, varies between 5.5‰ (last glacial maximum) and 9.5 ‰ (at present) in samples from the Dome C ice core. Based on this change in the deuterium excess, it is estimated that the change in the temperature at the source region, assumed to be mainly the Indian Ocean at about 40° S, is roughly 4.5°C between the last glacial maximum and the present warm epoch (Stenni et al. 2001).

The δ-values of ^{18}O and ^{2}H not only vary with long-term temperature variations, but also with seasonal temperature changes. δ-values are lower in winter than in summer precipitation. This can be used to identify annual layers in ice cores. However, for ice cores from the interior of the Antarctic Ice Sheet, the accumulation rates are so small, that these seasonal variations are not preserved. Another way to determine ice core chronologies is to use ice flow models. For such models an accumulation history is needed. A first approximation to establish such an accumulation history is to assume that accumulation rates are proportional to the derivative of the water vapor saturation pressure at the precipitation site and, therefore, a function of the local temperature, which can be estimated based on the isotope records (Jouzel et al. 1987). Accumulation rates during ice ages were only about 50% of those at the present time.

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See also **Atmospheric Gas Concentrations from Air Bubbles; Climate; Climate Change; Climate Modelling; Climate Oscillations; Ice Ages; Ice–Atmosphere Interaction and Near Surface Processes; Ice Chemistry; Ice Core Analysis and Dating Techniques; Paleoclimatology; Pollution Level Detection from Antarctic Snow and Ice; Precipitation; Snow Chemistry; Snow Post-Depositational Processes; Temperature; Volcanic Events; Vostok Station**

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ITALY: ANTARCTIC PROGRAM

Italy signed the Antarctic Treaty in 1981. Four years later, the Italian Parliament approved a law that established the National Programme of Antarctic Research (PNRA). The PNRA planned research activities from 1985 to 1991. The purpose of this activity was to make Italy a Consultative Party to the treaty, considering the enormous potential for the research work that could be performed in the continent. Already some Italian explorers and scientists had been to Antarctica in the second half of the nineteenth century.

In 1991 a new law was approved that extended the duration of the Antarctic activities with programs of 5 (now 3) years. The PNRA is being continued under the authority of the Ministry for Education, Universities and Research (MIUR). The PNRA includes research activities in many fields, including Earth sciences, atmospheric physics, cosmology, biology, oceanography, environmental sciences, and technology. In the course of its development, the PNRA has moved more and more towards multidisciplinary studies of global phenomena.

ENEA, the Italian Government Agency for New Technologies, Energy and Environment, has implemented the Antarctic programme for its first 17 years. In 2002 the organisation of the PNRA was modified: a consortium of four national agencies for the implementation of the PNRA was established. The agencies and their shares are ENEA (28%), National Research Council (24%), National Institute for Geophysics and Volcanology (24%), and Institute of Oceanography and Experimental Geophysics (24%).

A number of ministries are involved in the PNRA, as well as universities and research institutes. The Ministry of Defence gives a contribution in the training of candidates, the Navy performs hydrographic surveys, the Italian Air Force gives meteorological support and, when available, provides a C-130 for air transport from New Zealand to Antarctica. The Italian Foreign Office coordinates the Italian presence in the Antarctic Treaty Meetings.

Many Italian scientific activities are performed in cooperation with other countries, and by Italian law 20% of the research must be carried out with international cooperation. The same law initiated research in the Arctic in order to compare similar situations in the two hemispheres, and eventually a small research station was established in Svalbard.

From 1985 to 2004, PNRA oversaw nineteen expeditions, one each year. In 1985, a number of Italian scientists were sent to Argentine and Australian stations to gain experience in Antarctic work. The construction of the first research station, the site of which had been selected during the 1985–1986 expedition to the Ross Sea region, was begun in the second expedition. It was named Terra Nova Bay (TNB) Station and located at 74°42′ S, 164°06′ E. In 2004 its name was changed to Mario Zucchelli Station (MZS) for the man who was manager of the PNRA for 17 years. The station covers approximately 7000 m^2, and in addition to standard equipment has a sea-water desalination facility and wastewater treatment. The tank farm holds 1.8 million litres of fuel. To date, the station has been inhabited only in summer (November to March).

In the second expedition, besides the construction of TNB, the first research activities, mostly in Earth sciences, were begun. That made possible the admission of Italy as a Consultative Party to the Antarctic Treaty (1987). In 1988 Italy became a full member of the Scientific Committee on Antarctic Research. The second station, Concordia, was built more recently in cooperation with the French. It started operation in 2004–2005, with its first wintering personnel in 2006.

The following years saw the progressive enlargement of TNB and the broadening of the spectrum of scientific activities. In the third expedition (1987–1988) there was the first oceanographic and marine biology survey of the Ross Sea, while the ship OGS *Explora* performed the first of ten geophysical campaigns. From the fifth expedition, a fast connection between New Zealand and TNB was established, using a Hercules C-130.

During the sixth expedition (1990–1991), an automatic system was installed at TNB, capable of running a number of scientific experiments and transmitting the results to Italy. The system allows the data collection when the station is not manned during the Antarctic winter. The seventh and eighth expeditions were reduced in both size and duration, because of a delay in funding. However, the observatory activities at TNB continued normally and a large refueling of the station was possible. In the eighth year there was also a mission on the Antarctic Plateau in the direction of Dome C, for a distance of 350 km, using tracked vehicles. This was the first mission for a project that continued later with the establishment of a camp for fifty people at Dome C, where the European Project for Ice Coring in Antarctica (EPICA) was implemented. This project was nearly concluded in 2002–2003, having recovered ice cores about one million years old. This will allow the reconstruction of climate going back to that age. At Dome C, during the activity for EPICA, Station Concordia was constructed. This exceptional site has an elevation of about 3230 m above sea level and is located approximately 1200 km from the coast. The year-round base, made of two interconnected steel cylinders, will be an ideal site for studies in Sun–Earth relationships, astronomy and astrophysics, seismology and atmospheric physics, available to scientists of all interested countries,

The 1996–1997 expedition involved the largest number of people (340), thus becoming a test of Italian science and logistics after 10 years of Antarctic experience. Oceanography was the main subject of this expedition, with a programme on the ecology of the Ross Sea and the launch of long-term monitoring on the penguin colony at Edmonson Point. Another important international programme in this expedition was the Cape Roberts Project on paleoclimate, from recent to Oligocene (about 35 Ma). It consisted in the drilling of the sea bottom from a sea-ice platform.

The regular utilisation of Twin Otter light transport plane, for the flights connecting TNB and Dome C started during the eleventh expedition.

From 1998 to 2000 there was important international cooperation. While the ice drilling at Dome C reached a depth of 786 m, at the US McMurdo Station there was the successful implementation of the international project Boomerang (Balloon Observation of Millimetric Extragalactic Radiation and Geophysics) that collected data on the origin of galaxies. The International Trans-Antarctic Scientific Expedition collected ice samples and data along a 1152 km line between TNB and Dome C. The Cape Roberts Project was successfully concluded with the collection of a rock core 939 m long. The Airborne Polar Experiment performed a series of flights inside the polar vortex measuring in situ the seasonal decrease of the ozone layer.

Meteorites have been collected from the ice cap not far from TNB in several summer campaigns. In the nineteenth expedition, they amounted to about 5 kg.

An ice-strengthened vessel (M/V *Italica,* 5600 tons) resupplies the coastal station with heavy cargo and fuel, in addition to supporting research at sea and hydrography. About ten flights of the Hercules link MZS to New Zealand just before the beginning of the summer season. One or two Twin Otters are used to link MZS to Concordia, heavy loads usually reaching Concordia from the French station Dumont d'Urville on tracked vehicle convoys. Two to four helicopters carry scientists to local surveys and sampling. Most of the transportation is made on a charter basis. The OGS *Explora,* which is owned by an institute based in Trieste, makes marine geophysics surveys in the Ross Sea, around the Antarctic Peninsula and in the South Atlantic.

The scientific production of the Italian programme amounts (at this writing) to some 2040 papers. The PNRA's annual budget from 1999 to 2003 was typically around €25 million, ranging from a minimum of €21.4 million in 1999 to a maximum of €29.7 million in 2001. It includes core science, operation and logistics, investments, overheads such as costs for the headquarters and part of personnel, the normal salaries of the scientific personnel being paid by the home institutions.

Pietro Giuliani and R. Cervellati

See also **Antarctic Treaty System; France: Antarctic Program; McMurdo Station; Ozone and the Polar Stratosphere; Scientific Committee on Antarctic Research (SCAR); United States: Antarctic Program**

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J

JAPAN: ANTARCTIC PROGRAM

Start and Preparation for Organization

Japan resumed its activities in Antarctica on the occasion of the International Geophysical Year (IGY), after its first expedition by Nobu Shirase in 1911–1912. Present Antarctic programs of Japan have been continuing nearly 50 years and developing in accordance with changes of international schemes, administration systems, logistic facilities, etc.

The Science Council of Japan (JSC) established the National Committee for the Third International Polar Year in June 1952 in response to the call for participation in research programs in the International Polar Year (IPY). The government of Japan decided formally to join in international Antarctic research in the IGY and established Headquarters for Japanese Antarctic Research Expedition, consisting of executive officers of governmental agencies concerned and scientific advisors, chaired by the minister of the Ministry of Education (now the Ministry of Education, Culture, Sports, Science and Technology, MECSST) in November 1955. It has been responsible for the administration of the expedition and for approval of all programs, both scientific and logistical, since its establishment. The Antarctic Special Committee of JSC, which became independent from the IGY Committee in October 1955, worked on planning the research programs consisting of upper-atmosphere physics, meteorology, solid earth geophysics, geology, physical geography, glaciology, oceanography, and cartography for the first year of the 3-year program. The biological program was added in the second year. Researchers were dispatched from national universities and governmental agencies such as Radio Research Laboratories, Meteorological Agency, Hydrographic Office, and Geographical Survey Institute. The logistics plan, including construction of station buildings, telecommunication facilities, electricity system, etc., was also made by the committee. Logistics support people were selected mainly from private companies. However, all expedition members were employed by the government.

IGY and Expedition Ship *Soya*

Ice-strengthened R/S *Soya* of the Maritime Safety Agency sailed for Prins Harald Kyst (Prince Harald Coast), East Antarctica, from the Port of Tokyo 8 November 1956 for the first time. The Japanese Antarctic Research Expedition I (JARE-I) landed on the east coast of Lützow-Holmbukta (Lützow-Holm Bay) and constructed and opened Syowa Station. The IGY research program of Antarctica was extended for some years and finally semipermanently through the International Geophysical Cooperation by international agreement via the Antarctic Treaty in 1959. However, the operation of Japan was interrupted because the institution for conducting activities in

Antarctica was of provisional nature at that time and the expedition ship became decrepit. Syowa Station was closed 8 February 1962. The main scientific results in this first stage (JARE-I to JARE-VI) were the acquisition of basic data on the following: climate, aurora, cosmic ray, ionosphere, geomagnetism, and seismic activity at Syowa Station; bedrock and glacial geology of newly discovered Yamato Mountains and of coastal areas; glaciology, including explosion seismology; and mapping.

Establishment of Base and Operation with a New Icebreaker

The government of Japan decided to resume Antarctic research in August 1963 and began necessary preparations. Syowa Station was reopened formally 1 February 1965, with an agreement for the construction of the icebreaker *Fuji* and the establishment of a permanent national organization as a core of polar research, which has been conducted by researchers from universities and national institutes since IGY.

Science programs were divided into two categories for their appropriate operation and management: "research projects" and "routine observations." The former includes aurora observation, atmospheric sciences, glaciology, geology, and biology. These programs are to be conducted by scientists mainly from universities. The latter consists of routine meteorological observations, ionosphere observation, seismic monitoring, geodesy and cartography, and oceanographic observations on board the expedition ship. Several governmental agencies carry out routine observations: Meteorological Agency for meteorological observations, Radio Research Laboratories for ionosphere observation, Geographical Survey Institute for geodesy and cartography, Hydrographic Office for physical and chemical oceanography and for tidal observation at Syowa Station, and Polar Research Division of National Science Museum (Polar Research Center afterwards) for seismic monitoring and biological oceanography.

Main research projects of the early stage (JARE-VII to JARE-XIV) after resumption of expedition were an inland over-snow traverse to and from the South Pole in 1968–1969, rocket observation of aurora in 1970–1973, and glaciological fieldwork including wintering at a small inland station, Mizuho, in 1969–1973.

The National Institute of Polar Research (NIPR) was established by MECSST as one of national institutes for joint use by universities in September 1973. It grew out of the Polar Research Center of the National Science Museum. It has been the national center both for polar research and for organization and operation of Antarctic expedition since its start.

Research programs were made in advisory planning committees set out in NIPR. Committees were settled to cover four fields: upper-atmosphere physics, meteorology and glaciology, earth sciences, and biology. Each committee was chaired by a scientist from an organization (mainly from a university) other than NIPR. Routine observation programs were planned by organizations concerned respectively. Programs for logistics support such as renewal of living quarters and telecommunication facilities were made by the logistics advisory planning committee. The Headquarters for JARE approves all research programs and operations in the Antarctic region at its general assembly every year, though programs have been mostly multiyear ones.

Main programs and results from 1972–1974 to 1982–1984 (JARE-XV to JARE-XXIV) were rocket observation of aurora as a part of International Magnetosphere Study, marine biology as a part of BIOMASS programme (some research ships from universities and a governmental agency participated in this program), micrometeorology and glacial climatology in POLEX SOUTH programs, explosion seismology for crust and upper mantle study, and meteorite searches. The discovery of the "ozone hole" in 1982 and collection of many "Yamato Meteorites" are noteworthy among various results.

Age of New Development

The new icebreaker *Shirase* was placed in commission in November 1983, relieving the duty of *Fuji*. The capability of *Shirase* for ice navigation and cargo transportation made it possible to introduce programs that need large-scale operation. Construction of Asuka Station began near the foot of the Sür-Rondane Mountains in 1984–1985 in order to carry out earth science and biology field programs. Year-round meteorological and geophysical observations were also carried out until 1991. The first deep ice coring was carried out in winter 1995–1996 at Dome Fuji station, which was constructed at the summit of the dome 3810 m above sea level. A 2500 m long ice core was obtained. The second deep ice coring started in the 2003–2004 season in order to study global environmental changes in the last 800,000 years, using international intercontinental air transportation system. Long-term earth science investigations of Enderby Land, 400 km east of Syowa Station, were carried out for study of the crustal evolution of one of the oldest complexes of the world. Various investigations in upper atmosphere physics such as receiving of signals from satellites by a large parabola antenna and polar patrol balloon observations are being conducted at Syowa Station. Continuous gravity measurement using a superconductivity gravimeter, GPS observation, and tidal observation are being carried out for the purpose of global monitoring of change of the Earth. The Intelsat system was introduced into Syowa Station and started service February 2004. The system serves scientists for real-time research as well as for private telecommunication. The main research projects in 2005–2007 are as follows: (1) continuation of deep ice coring at Dome Fuji Station, (2) Late-Cenozoic Antarctic ice sheet history and global change, (3) geophysical mapping around Syowa Station (Japan-Germany collaboration study on airborne geophysics), and (4) time-serial studies on biological processes and greenhouse gases in the seasonal sea ice zone.

In addition to the above, NIPR carried out small-scale joint programs as part of national programs: US–Japan Search for Meteorites in Victoria Land from 1976–1977 to 1979–1980 and US–New Zealand–Japan Mount Erebus Eruption Mechanism Studies from 1980–1981 to 1985–1986.

Nongovernmental Programs

Besides governmental programs, Japanese researchers from several universities and institutes conducted geochemical field investigations in the Dry Valleys region in Victoria Land from 1963–1964 to 1986–1987. Transportation and other logistical support were provided by Division (now Office) of Polar Programs, NSF of the US, and by Antarctic Division, DSIR of New Zealand (now NZ Antarctic Programme). Japan Polar Research Association, a nongovernmental foundation, continued to provide grants for fieldwork. The Dry Valley Drilling Project (DVDP), which became an important part of the said programs, was performed jointly by the US, New Zealand, and Japan. The government of Japan shared the expense.

Reform of NIPR

NIPR reformed its administration system in April 2004, in accordance with the reformation of national universities and institutes by the legislation. The system for planning and administration of research programs is expected to be improved in the near future.

Governmental Budget

Budget for governmental programs is variable every year due to change of programs, degree of ship repair, etc. The budget for 2004 fiscal year in round numbers was: for research projects, 600 million Japanese yen (US$5.6 million); for routine observation, 170 million yen (US$1.6 million); for logistics except ship operation, 750 million yen (US$7.0 million); for ship operation, 2.3 billion yen (US$21.5 million); and for other expenses including exchange of scientists under the Antarctic Treaty, 100 million yen (US$0.9 million). 30 billion yen (US$28 million) was appropriated for renewal of a large helicopter and an icebreaker as part of multiyear funding.

Yoshio Yoshida

See also **Antarctic Treaty System; Dry Valleys; International Geophysical Year; Japanese Antarctic Expedition (1910–1912); Ozone and the Polar Stratosphere; Shirase, Nobu**

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NIPR publishes five journals in English: *Advances in Polar Upper Atmosphere Research, Polar Meteorology and Glaciology, Polar Geoscience, Antarctic Meteorite Research,* and *Polar Bioscience.* It also publishes *Antarctic Record* (*Nankyoku Shiryo* in Japanese) comprising English and Japanese papers and reports in three volumes annually; *JARE Data Reports* in ten fields in English; *Memoirs of National Institute of Polar Research,* an occasional publication in six fields in English; and the *Antarctic Geological Map Series.*
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JAPANESE ANTARCTIC EXPEDITION (1910–1912)

The Japanese Antarctic Expedition, which sailed aboard *Kainan-maru* from Japan on December 1, 1910, had been sent on its way by a crowd of 50,000 well-wishers. Lieutenant Nobu Shirase's ambition to be a polar explorer had caught the popular imagination of a country eager to be regarded as an equal by the West and frustrated by the economic and territorial outcomes of military victory in two wars. Shirase's backers included former prime minister Count Shigenobu Okuma, many prominent figures of the Japanese establishment, and large sections of the popular press. However, the government refused to release substantial funds voted to the expedition, and the explorers were dependent on donations from wealthy individuals and public subscription.

The aim of the expedition was to land on the eastern side of the Ross Sea, and set out the following spring hoping to reach the South Pole before Robert Falcon Scott—like the British, Shirase and his backers were still unaware of Roald Amundsen's expedition. The departure of the expedition was delayed by problems obtaining a suitable ship, and lack of space meant using dog sledges for transport instead of horses. Thirty dogs and two Ainu drivers, Yasunosuke Yamabe and Shinkichi Hanamori, joined the expedition from the Japanese territory of Karafuto on sub-Arctic Sakhalin Island, but when Captain Naokichi Nomura brought *Kainan-maru* into Wellington Harbour in New Zealand only six dogs were left alive. After taking on fresh supplies, they sailed on February 11, 1911, setting course for the Ross Sea at a date when most other vessels would have been leaving Antarctic waters.

The first ice was seen on February 28, and on March 6 they sighted the mountains of Victoria Land. Off the Possession Islands the sea started to freeze around them, with floes up to 2 feet (61 cm) thick. Near Coulman Island on March 12 they reached 74°16′ S, 172°07′ W before turning the ship around in the ice to escape from the pack. At a meeting on March 15, they decided to set course for Australia, and, after a stormy voyage in a damaged ship, they dropped anchor in Sydney Harbour on May 1, 1911.

The Australian government granted them official status, and they erected their prefabricated hut at Parsley Bay Reserve on Sydney Harbour. With the support of Professor T.W. Edgeworth David, the famous Australian explorer and academic, an initially mixed reception from the Sydney press was soon overcome. While *Kainan-maru* was undergoing repairs, Nomura returned to Tokyo, Shirase remaining with his men in Sydney.

Nomura brought fresh supplies and twenty-nine dogs from Japan, and *Kainan-maru* sailed from Sydney on November 19, 1911. They now planned to land on the Ross Ice Shelf between 160° and 170° W and explore the area to the southeast, land a party in King Edward VII Land, and use *Kainan-maru* to explore the seas to the east. They saw the first iceberg on December 11, and struggled through the pack until sighting the mountains of Victoria Land on December 3. They were held up by ice again before their first landing on January 16, 1912, at 78°17′ S and 162°50′ W in Kainan Bay, although the surface was too crevassed to allow access to the interior.

Kainan-maru proceeded west, and moored to the ice in the Bay of Whales late on January 16. While supplies and equipment were being unloaded, visits were exchanged with the crew of *Fram,* waiting in the bay for Amundsen's return from the South Pole. By a tremendous effort they transported everything to the top of the 200-foot (60 m) ice cliff of the Barrier in less than 28 hours, and established a base camp at 78°33′ S, 164°22′ W.

The sledging party that set off southeast across the Ross Ice Shelf the following day was aptly named the Dash Patrol. Shirase led his four companions on a short but probably record-breaking journey. On January 28 they reached 80°05′ S after travelling approximately 147 miles (237 km) in nine days through very mixed weather, having covered just over 56.5 miles (91 km) the day before, much of it uphill. They raised the Japanese flag and buried a copper casket containing the names of everyone who had contributed to the expedition's funds, before starting back to the base. Their return journey was even more remarkable. In just over nine hours on January 28 they sledged 70 miles (112 km), covering the remaining 78 miles (125 km) in two main stages to arrive at the base camp early on January 31. Their success was largely due to the skill and efforts of the Ainu dog drivers, Yamabe and Hanamori.

In the meantime *Kainan-maru* had sailed east for King Edward VII Land on January 19. Four days later it was moored to the ice at 76°56′ S, 155°55′ W, and Genzo Nishikawa and Chikasaburo Watanabe climbed to the foot of Scott Nunataks, walking more than 37 miles (60 km) in 30 hours with nothing but their coats, a tin of condensed milk, and some biscuits. Next day *Kainan-maru* sailed east again, reaching 76°06′ S, 151°20′ W on January 26, besting Scott's 1902 record in that direction by nearly 11 miles (17.3 km). Returning west it paused from January 29 to 30 at 77°50′ S, 158°40′ W in Okuma Bay to collect rocks embedded in icebergs, before picking up the main party from the Bay of Whales on February 4.

After another stormy voyage across the Southern Ocean, the expedition arrived in Wellington on March 23. Shirase returned to Japan by steamer to organise payment for the men and develop the motion picture that they hoped would defray the expedition's debts. *Kainan-maru* arrived in Tokyo Bay on June 20, 1912, to a hero's welcome with a lantern parade through the city, and Shirase and Nomura were granted an audience with the Imperial Family.

The geological and biological samples collected in Antarctica were analysed by researchers at Tokyo Imperial University and exhibited throughout the country, and at least five separate accounts of the expedition's achievements were published. Sadly, Emperor Meiji's death shortly after their return eclipsed all other news from Japan, and the achievements of the Japanese Antarctic Expedition did not receive the international recognition they undoubtedly deserved.

HILARY SHIBATA

See also **Amundsen, Roald; British Antarctic *(Terra Nova)* Expedition (1910–1913); David, T.W. Edgeworth; Dogs and Sledging; Norwegian *(Fram)* Expedition (1910–1912); Ross Ice Shelf; Scott, Robert Falcon; Shirase, Nobu; South Pole**

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K

KELP GULL

Kelp gulls *Larus dominicanus* are a large slate-black-and-white gull with a 1.2- to 1.4-m wingspan and a body mass of approximately 1.0–1.4 kg; males are typically 10%–15% larger and heavier than females. Individuals take 3 years to reach maturity. Their plumage is characteristic and diagnostic for first-year and second-year birds; third-year and adult birds are indistinguishable. First-year birds have a streaked or speckled dark-brown-and-grey plumage, with dark legs and a dark bill. Second-year birds have a "salt and pepper" plumage, with pale bill, streaked or patchy white and bleached brown feathers, and dark legs. Adult birds are slate-black above on the wings and body, and white below, with pale lemon-straw-coloured legs, a pale-yellow bill with prominent red spot on the lower mandible, and a yellow eye with an obvious red orbital ring.

Breeding populations of kelp gulls are present on all Southern Hemisphere continents, and on most islands and island groups south of the Subtropical Front. The southernmost breeding record is 68° S on the Antarctic Peninsula. They are absent from the highest-latitude islands in the Southern Ocean (Balleny Islands and Scott I and Peter I Øy) and from the warm-water Île Amsterdam, and Tristan da Cunha and Gough Islands. The current global population is estimated at more than 1.2 million breeding pairs, of which more than 1 million are believed to breed in New Zealand. Breeding populations have increased in South America, South Africa, and New Zealand in the recent past and are believed to have established in Australia in the late 1950s. Breeding populations are year-round residents with high fidelity to nest sites—there is some evidence of intraseasonal migration by individuals. There is some postbreeding dispersal, with sightings of birds of all ages away from natal sites. Studies have speculated that the Australian population originated in New Zealand. Extent of dispersion appears to be colony specific, with individuals at some breeding colonies present year round. There is no evidence of movements away from sub-Antarctic islands. Antarctic Peninsula colonies are occupied if food is available.

Breeding season varies with locality and latitude, with southerly localities later in breeding-season events than northerly sites, with eggs laid as early as August in Australia and as late as December on the Antarctic Peninsula. Most sub-Antarctic islands' populations lay eggs in November and December. The clutch is typically three eggs, and nests are characteristically close to the coast on sub-Antarctic islands and on the Antarctic Peninsula. Nests are constructed from vegetation and may be almost a metre in diameter and approach half a metre in height. Both adults incubate the eggs, brood, and feed the chicks. Few banding studies have been conducted to establish longevity but kelp gulls are likely to reach 20 years. Age at first breeding is 3 or 4 years, and most birds breed annually.

Nesting can be solitary to colonial. Breeding colonies on sub-Antarctic islands and on the Antarctic Peninsula are typically small to medium in number. Breeding pairs are monogamous and most are maintained from one breeding season to the next. Courtship feeding initiates pair-bond reestablishment during winter months. Breeding territories may be maintained interseasonally and there is a high fidelity to nest site. Postbreeding flocks comprising all age classes form once chicks have fledged. Nesting behaviour is easily disturbed by humans.

Kelp gulls are omnivorous, and feed primarily in the intertidal region, although individuals will scavenge at carcasses and beach-washed material. Kelp gulls will occasionally follow fishing vessels for discards. Individuals will attend breeding sites of seals to scavenge placentae and have been observed feeding on discharged sewage. Their primary food comprises molluscs, crustaceans, and fish, but this is dependent on location and seasonal food availability. Birds are able to dive briefly to obtain food from below the water surface. Kelp gulls will drop molluscs onto rocks to break the shells. Birds may occasionally kleptoparasitise, stealing food from conspecifics or from individuals of other species such as terns and penguins.

Eric J. Woehler

See also **Amsterdam Island (Île Amsterdam); Antarctic Peninsula; Balleny Islands; Fish: Overview; Gough Island; Peter I Øy; Terns: Overview**

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KERGUELEN ISLANDS (ÎLES KERGUELEN)

Îles Kerguelen (48°27′ to 50°00′ S, 68°27′ to 70°35′ E) are located in the in the Southern Indian Ocean, 1500 km southeast of Africa and 1800 km southwest of Australia. The archipelago comprises a main island (Grande-Terre) and about 300 offlying islands, islets, and rocks. The total area is about 7200 km^2. The coastline (about 2800 km) is deeply distorted by inlets into numerous peninsulas and fjords.

High mountains occur in the west part of the archipelago. The maximum height is Mont Ross (1850 m asl). By contrast, extensive plateaus with many ponds constitute the eastern side. Between these two sides, deep glacial valleys and numerous rivers and lakes are present, a heritage of past glacial events and strong tectonic activity. The islands are of volcanic origin and the rocks are mainly of basaltic composition, the oldest being more than 25 million years old. An exception is visible on the southwestern part of the archipelago, Péninsule Rallier du Baty, where different metamorphic rocks are dominant (granites, gabbros). The Cook ice cap, 50 by 20 km, is the remains of an ice sheet that formerly covered the major part of the archipelago. Numerous other small glaciers occur in the west.

Climate, as recorded by Météo-France at Port-aux-Français since 1951, is characterized by cool temperatures (3.1°C in winter, 6.5°C in summer), moderate precipitation (770 mm per year), and strong westerly winds. However, the relief on the west creates a foehn effect that is responsible for a strong gradient of precipitation, varying from more than 3500 mm per year on the west coast to less than 700 mm per year in several places in the Golfe du Morbihan. In addition, there is evidence of drastic changes in the recent climate conditions: temperatures have increased by 1.3°C since the mid-1970s, and precipitation has been halved during the same period. As a consequence, all the glaciers are currently retreating and, at least at low altitude, summer droughts threaten the native biota, which has never experienced such environmental conditions.

The native flora comprises twenty-nine vascular plant species: twenty-two phanerogams and seven pterydophytes. The only endemic species is *Lyallia kerguelensis* Hooker f. (Hectorelliaceae). Most of the other species are sub-Antarctic species and grow in the other islands of the southern Indian biogeographic province, namely Marion, Prince Edward, Crozet, and Heard islands. The cosmopolite blue grass *Poa annua* is the only species with an uncertain status: it occurs in most of these islands but was likely early introduced by man, as suggested by the high rate of its current extension in the most visited areas. Beside these vascular plants, numerous bryophyte and lichen species, probably several hundred, are present but very few studies have been carried out on these groups.

Vegetation varies considerably along the altitude. Up to 250 m asl, the Kerguelen cabbage (*Pringlea antiscorbutica,* Brassicaceae), *Acaena magellanica* (Rosaceae), and the grass *Festuca contracta* usually dominate in moist habitat with deep organic soils. Cushions of *Azorella selago* (Apiaceae) occur on moraine slopes and exposed plateaus. *Dechampsia antarctica* and *Agrostis magellanica* occur along stream banks and in bog areas. Above the plateaus, open feldmark vegetation of grasses, ferns, mosses, and lichens can occur, but many high areas are devoid of vegetation.

In addition to these native species, sixty-nine alien species were recently recorded. Only seven are invasive and widely distributed within the archipelago

(Cerastium fontanum, C. glomeratum, Sagina procumbens, Stellaria media, Taraxacum erythrospermum, T. officinale, and *Poa annua),* while the remaining persistent species are linked with sites that are or have been intensively used by humans. Most of these introduced plants are European and are favoured by the current trends in the climatic conditions.

About 150 invertebrate species are known from Îles Kerguelen, some of them endemic to the Southern Indian Ocean sub-Antarctic province. The insect fauna show spectacular morphological and physiological adaptations, such as wing reduction or starvation capacities. The wingless fly *Anatalanta aptera,* for instance, living in bird colonies, is able to survive without food during several months in winter, waiting for the return of birds. The invertebrate fauna are dominated by decomposers (numerous earthworms, collembola, diptera), with few herbivores (weevils) and rare predators (two spider species and one staphylinidae). This disharmony in the trophic structure of the invertebrate community is responsible for its high sensibility to introduction of alien species: the carabid beetle *Oopterus soledadinus,* accidentally introduced in the early twentieth century, is currently spreading in several littoral sites of the archipelago, where it constitutes a serious threat for the native invertebrate fauna. A total of thirty introduced invertebrate species have been recorded, only a few of them being widely distributed: earthworms *(Dendrodrilus rubidus tenuis),* diptera *(Calliphora vicina, Fucellia maritima),* and aphids *(Myzus ascalonicus, Rhopalosiphum padi).*

The islands host thirty breeding species of bird, the most common species including king penguin, macaroni penguin, rockhopper penguin, wandering albatross, Kerguelen shag *(Phalacrocorax verrucosus),* sub-Antarctic skua, kelp gull, Kerguelen tern, Antarctic tern, a pintail *(Anas eatoni)* endemic to Îles Crozet and Îles Kerguelen, and a black-faced sheathbill *(Chionis minor minor)*. There are also numerous petrels, including the Cape petrel, white-headed petrel, Kerguelen petrel, blue petrel *(Halobaena caerulea),* white-chinned petrel *(Procellaria aequinoctialis),* Wilson's storm petrel, black-bellied storm petrel, Antarctic prion, South Georgian diving petrel *(Pelecanoides georgicus),* and Common diving petrel *(P. urinatrix)*. Two species of marine mammal breed on the islands: southern elephant seal and Antarctic fur seal.

Twelve alien vertebrate species have been introduced, five salmonid fishes, and seven mammals (mouse, rat, rabbit, sheep, mouflon, reindeer, and cat). These mammals have considerable impacts on the indigenous ecosystems naturally devoid of mammalian herbivores or carnivores: for example, only the rosaceae *Aceana magellanica* survives on islands where rabbits are present, rats and mice have a strong impact on invertebrate communities, and cats eat several thousands birds each year. Rabbits and rats have been recently removed from experimental islands in conservation actions.

Îles Kerguelen were discovered by Captain Yves-Joseph de Kerguélen-Trémarec, who made two claims: on February 12, 1772, and again during his second expedition in December 1773. They were explored by Captain James Cook in 1776, who named them after Kerguélen (with the alternative name Islands of Desolation). Sealers, whalers, and several scientific expeditions visited the islands in the nineteenth century. In 1908 a sheep farm and a whaling station were established at Port Jeanne d'Arc, continuing until 1930. A scientific station was established at Port-aux-Français in 1950. It hosts about one hundred people in summer and fifty in winter. Today, the fishing activity (the two main fish species concerned are *Notothenia squamifrons and Champsocephalus gunnari*) is strictly controlled in terms of authorized ships and amount of catches.

YVES FRENOT

See also **Antarctic Fur Seal; Antarctic Prion; Antarctic Tern; Cape Petrel; Climate; Climate Change; Conservation; Cormorants; Crested Penguins; Crozet Islands (Îles Crozet); Fish: Overview; Fisheries and Management; France: Antarctic Program; France: Institut Polaire Français Paul-Emile Victor (IPEV) and Terres Australes et Antartiques Françaises (TAAF); Heard Island and McDonald Islands; Insects; Kelp Gull; Kerguelen Tern; Kerguélen-Trémarec, Yves-Joseph de; King Penguin; Lichens; Macaroni Penguin; Mosses; Petrels: Pterodroma and Procellaria; Precipitation; Prince Edward Islands; Sheathbills; Southern Elephant Seal; Sub-Antarctic Skua; Vegetation; Wandering Albatross; Wilson's Storm Petrel**

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KERGUELEN TERN

Kerguelen terns *(Sterna virgata)* only breed on the southern Indian Ocean islands of the Prince Edward Islands, Îles Crozet, and Îles Kerguelen. Nonbreeders have been seen on islands in these island groups that are not used by breeding birds (e.g., Île aux Cochons). About 50 pairs breed on the Prince Edward Islands, more than 150 pairs on Îles Crozet, and 1500 to 2000 pairs on the Îles Kerguelen archipelago. The populations on the Kerguelen archipelago are growing because of the introduction of salmonid fish, but on Îles Crozet, the Kerguelen tern is threatened by introduced black rats *Rattus rattus* and cats *Felis catus*.

Kerguelen terns are usually only seen near their breeding islands. Most birds feed within 2 km of the shore and few go farther offshore. The birds are most frequently seen in open waters in the surf zone or along sheltered parts of the coastline, but are sometimes also seen in the littoral zone. Kerguelen terns are one of the few species that can be seen inland, some kilometres from the coast, where they nest in terrestrial habitats, such as rocky or sparsely vegetated swards. Kerguelen terns are sedentary and do not disperse far. Juveniles have been observed with adults, not only after fledging but also during the winter in the seas around breeding grounds. Sometimes they form mixed-species flocks with Antarctic terns *S. vittata*.

Individuals nest in small colonies, generally on flat and gently sloping ground on exposed clifftops, rocky islands, hills, or plateaux. Other places used are gravel plains, valleys, river flats, and occasionally shell or pebble beaches. Sandy beaches are avoided. The breeding places are characterized by scree and other stony debris, and the vegetation is sparse or closely cropped. Nests have been found up to 100 m above mean sea level and, at the furthest, 2.4 km from the coast.

The clutch size for Kerguelen terns differs among islands. On Îles Crozet, they usually lay one egg, on Marion I one or two, and on Îles Kerguelen two. Incubation lasts 24 days; the chicks fledge after 31 to 39 days but remain dependent on their parents for a further 20 days. The timing and duration of breeding varies between years and among breeding sites. After their first visits to the colonies, Kerguelen terns lay their first eggs in August or September, on Îles Crozet from early October to early January, and hatchings occur from early November to late January. For courtship feeding, the male brings a fish or sometimes crustaceans or insects to the female.

Kerguelen terns feed on fish, crustaceans (amphipods, isopods, and crabs), and other terrestrial or marine invertebrates (annelids, spiders, insects). The food changes seasonally: in September they feed mainly on crustaceans, during incubation in November on fish, and during chick rearing in December mainly on terrestrial arthropods. They mainly forage in inshore marine waters, only occasionally venturing up to 2 km from the islands. The food is taken by plunging into the sea from 3 to 4 m above the surface. The terns prefer the surf zone along the coast and sometimes forage in the inshore beds of seaweed, in which they feed just below the surface of the water. At low tide some terns feed in shallow intertidal pools on stony as well as sandy beaches. In some cases during spring and summer, feeding also occurs in freshwater terrestrial wetlands near breeding colonies. These sites include fell meadows, damp meadows, bogs, and marsh terraces. Fishing in rivers has also been recorded. Sometimes the birds feed among closely cropped terrestrial vegetation. In terrestrial habitats, they forage both aerially and on the ground.

HANS-ULRICH PETER

See also **Antarctic Tern; Birds: Diving Physiology; Crozet Islands (Îles Crozet); Fish: Overview; Kerguelen Islands (Îles Kerguelen); Prince Edward Islands; Terns: Overview**

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KERGUÉLEN-TRÉMAREC, YVES-JOSEPH DE

Yves-Joseph de Kerguélen-Trémarec (1734–1797) was a Breton naval officer who had for years hoped to conduct a voyage of discovery to the southern oceans. He followed in the wake of well over two centuries of French explorers (Paulmier de Gonneville, Jules Marie Crozet, Marie-Joseph Marion-Dufresne, and Jean-Baptiste Bouvet de Lozier) who explored the southern seas. With the French government eager to follow up on the earlier discoveries of its explorers and extend its sphere of global influence, Kerguélen-Trémarec succeeded in obtaining approval for a voyage of exploration. He sailed from Lorient on the Breton coast of France on May 1, 1771 with instructions to sail south from Île de France (now Mauritius, 20°17′ S, 57°33′ E) to discover a continent south of Île St. Paul (38°55′ S, 77°41′ E) and Île Amsterdam (37°57′ S, 77°40′ E). Based on de Gonneville's reported landfall in 1503–1504 when he was blown south of the Cape of Good Hope, such a landmass was expected to be temperate and inhabited, and Kerguélen-Trémarec was to establish good relations and trade agreements with the inhabitants.

He departed from Île de France on January 16, 1772 with two vessels, *La Fortune* under his direct command, and *Le Gros Ventre* under François Alesno Comte de St-Allouarne. On February 12, Kerguélen-Trémarec sighted a small island and the following day a larger landscape at 49°40′ S, and 61°10′ east of Paris (longitude 2°20′ E). (Longitude determinations in Kerguélen-Trémarec's day were still imprecise, and the general position of 'les Kerguelen, now named after their discoverer, is 49°20′ S, 69°30′ E). Stormy weather separated the ships and prevented Kerguélen-Trémarec from landing, but St-Allouarne launched a boat under the command of a Breton named Boisguehenneue who was able to land at Sea-Lion Bay (now Anse du Gros Ventre) and took possession for King Louis XV. The land was named "La France Australe." Approximately 75 miles of coastline were examined, but due to poor conditions the men had to quit the area.

Upon his return to civilization, Kerguélen-Trémarec greatly exaggerated the significance of his land discovery. He delightedly described having found the central mass of the long-sought Antarctic continent and that it was favorably positioned as a convenient link to India, the Moluccas, China, and the South Seas. He predicted that the economic vitality of 'le de France would be tripled and that La France Australe would be so arable as to provide all the crops needed for 'le de France's inhabitants, thus obviating the need to resupply the island all the way from France. He claimed that La France Australe had abundant natural resources—wood, diamonds, rubies, marble, and more. Not only this, but if there were human inhabitants, they would be primitive and incapable of being offended, implying that they could be put to productive use without resistance.

His report engendered well-deserved skepticism, even ridicule, but he was persuasive enough, the latitudes were low enough, and France's interest in extending its dominion great enough that influential Frenchmen listened: the head administrator of 'le de France wrote enthusiastically that Kerguélen-Trémarec had discovered for France a whole new world. St-Allouarne had sailed directly to Australia after the landing at La France Australe, and thus no timely first-hand report of the bleak conditions ashore had reached France to counter Kerguélen-Trémarec's fantastic account. Kerguélen-Trémarec was awarded the esteemed Cross of St. Louis and outfitted for another voyage to the area, this time in three ships, *Le Roland, L'Oiseau,* and *La Dauphine*. The vessels sailed March 26, 1773 and were to proceed eastward between 40° and 60° S.

On this second voyage, the officers were inept; the ships arrived at the Cape of Good Hope in poor condition with many of the crew seriously ill. By now, St-Allouarne's account had reached France, and authorities were newly skeptical of Kerguélen-Trémarec's tales of the islands' temperate climate and natural riches. Kerguélen-Trémarec's sick men were replaced with poor substitutes, and the ships arrived at La France Australe on December 14, 1773 in unfavorable weather amid terrible conditions aboard. A landing was effected on January 6, 1774, not by Kerguélen-Trémarec, whose leadership seemed to be foundering, but by Charles de Rosnevet of *L'Oiseau*. Wildlife was abundant, but no humans were found inhabiting these inhospitable islands that were incessantly enshrouded in fog, whipped by gales, and pelted by rain. The men examined the islands more carefully, prepared crude charts, and returned to France.

Meanwhile, James Cook had completed a high-latitude circumnavigation; in February 1773 he passed well south of Kerguélen-Trémarec's position, thus proving that no land discoveries north of his latitudes constituted part of an Antarctic continent. Kerguélen-Trémarec had to admit the folly of all his earlier assertions, except the land discoveries per se. He fittingly named the island group the Land of Desolation. It is telling that Joseph Dalton Hooker, the young botanist on James Clark Ross' Antarctic voyage of 1839–1843, referred to Îles Kerguelen after a lengthy visit as one of the "most wretched spots on the globe."

Kerguélen-Trémarec arrived at Brest, France on September 7, 1773. A variety of charges were laid against him, including smuggling a woman aboard *Roland* for his personal pleasure, carrying goods to trade for his own benefit, failing in his responsibilities as leader, and professional misconduct. He was arrested, court-martialed, and imprisoned for 4 years. In some measure, however, he was eventually forgiven the transgressions of his ludicrous assertions and misdeeds, for the islands, about 300 in all, are collectively Îles Kerguelen in his honor, and have belonged to France since 1893.

Michael H. Rosove

See also **Amsterdam Island (Île Amsterdam); Bouvet de Lozier, Jean-Baptiste; Cook, James; Kerguelen Islands (Îles Kerguelen); St. Paul Island (Île St. Paul)**

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KILLER WHALE

The killer whale *(Orcinus orca)* is a toothed whale (suborder Odontoceti) in the order Cetacea (whales, dolphins, and porpoises); it is, in fact, the largest member of the dolphin family (Delphinidae). Also commonly referred to as "orca," it is the most widespread animal in the world, after humans. Although more common in high latitudes than in the tropics, it is found throughout the world's oceans.

The highly contrasting black-and-white pattern is easily the most familiar of any of the cetaceans, making the killer whale perhaps the most universally recognizable marine animal. The pattern is essentially black above and white below, with a prominent white eyepatch just above and behind the eye, and a large white flank patch that extends dorsally from the area of the vent, and then posteriorly along the flanks. The "saddle patch" is a pale gray area posterior to the dorsal fin that extends ventrally, and then anteriorly as a thin taper. Young calves have an orange tinge to all of the white-pigmented areas, which usually disappears within 1 year. Killer whales that live in close association with pack ice are often coated with a yellowish diatom film, giving them a brown-and-yellow appearance.

Killer whales are strongly sexually dimorphic and, among cetaceans, are second only to the sperm whale *(Physeter macrocephalus)* in the degree of physical differentiation between males and females. Adult males reach a total length of 9.0 m and females up to 7.7 m. Few have been accurately weighed, but a 6.75-m male weighed 5568 kg, and a 6.7-m female weighed 3810 kg. Neonate calves are 2–2.5 m long and weigh approximately 200 kg. Compared to females, adult males also have proportionately large extremities, including flukes, flippers, and dorsal fin. The impressive dorsal fin of an adult male can reach almost 2 m in height, nearly twice that of the female. Adults have ten to twelve (up to fourteen) teeth in the upper and the lower jaw; they are pointed and conical, and all have the same general shape (homodont).

Worldwide, there is only one species of killer whale recognized, and no named subspecies. It has become clear, however, that some killer whale communities (perhaps mainly in higher latitudes) include subpopulations that specialize on different prey and appear to be reproductively isolated. The formation of these "ecotypes" is correlated with a divergence in morphology, behavior, and vocalizations within sympatric killer whale populations, and may ultimately be responsible for initiating speciation events. For example, based on ecological and genetic differences, it has been suggested that the fish-eating and mammal-eating killer whale ecotypes in the northeast Pacific probably qualify as separate species (or at least subspecies), although no formal recognition has been suggested.

Based on catches from whaling vessels operating in Antarctica in the early 1980s, two groups of Soviet scientists independently described two new species of killer whales. They were named *Orcinus nanus* and *O. glacialis,* but their existence has been discredited and largely ignored by cetologists because the descriptions were inadequate and there are no extant holotypes (voucher specimens).

More recently, three distinct ecotypes of killer whales were described from field observations in Antarctica, and designated Types A, B, and C. Each of these ecotypes is readily identifiable at sea, and each appears to have distinct prey and habitat preferences. Type A appears to be the "typical" globally distributed killer whale. It is black and white, has a circumpolar distribution in Antarctica, lives in open water, and occurs in small groups (averaging around fourteen individuals). It apparently migrates south to Antarctica each summer to feed on Antarctic minke whales *(Balaenoptera bonaerensis)*. The minkes also migrate to Antarctica each summer, to feed on seasonal krill blooms, and Type A killer whales intercept them north of the ice edge.

The Type B killer whale also has a circumpolar distribution, but is especially common in waters around the Antarctic Peninsula. This form has a tripartite color pattern with a black dorsal cape, gray sides, and white underparts. It also has a noticeably large white eyepatch compared to the other forms. It forages in small groups (averaging approximately twelve animals), and hunts among loose pack ice where it has been seen to feed only on ice seals and elephant seals *(Mirounga leonina)*.

The Type C killer whale occurs mainly in East Antarctica. It also has a gray, black, and white color pattern, but the eyepatch is small and slanted. It forages in large groups (averaging 46 individuals, although groups of 300–400 have been reported), occurs in dense pack ice and among leads in fast ice, and has been observed feeding only on Antarctic toothfish *(Dissostichus mawsoni)*. During the winter, Types B and C have been observed both in Antarctic waters and in lower latitudes, leaving their migratory status unclear.

Although these three forms occupy adjacent and, at times, overlapping ranges, they do not occur in mixed schools and there have been no reports of intergrades (i.e., possible hybrids). This has led to the conclusion that they may represent two, or possibly three, separate species. Currently, it is not clear how these three forms relate to the two new species that were proposed by the Soviet scientists. The latter descriptions were so vague that it is impossible to determine whether the same or different species were being described, although in both cases "dwarf" forms were indicated. Recent measurements of Type C killer whales in the southern Ross Sea from aerial photographs indicate that they are on the order of 1.5–2 m shorter than the "regular" killer whales measured by Soviet whalers. Although this provides further evidence that there might be multiple species in Antarctica, additional data on genetics and morphology will be necessary to provide confirmation.

Nearly all that is known about the life history, behavior, social structure, and ecology of killer whales has come from ongoing studies in the northeast Pacific during the past three decades. Males there live an average of about 30 years (estimated maximum: 50–60 years); they attain sexual maturity at about 15 years, and continue to grow until they reach physical maturity at 21 years. Females live an average of 50 years (maximum: 80–90 years); they give birth to their first calf between 11 and 16 years of age (mean 15), and average about one calf every 5 years during a reproductive life span of about 25 years. After that, they enter a postreproductive period lasting from 10–30 years. The gestation period is 15–18 months, and calves can be born during any month of the year. Calves nurse for at least one year and are weaned probably between 1 and 2 years of age.

Killer whales generally live in stable groups of related individuals for their entire lives. Among fish-eating populations studied to date, the basic social organization is matrilineal: an older female lives with her sons and daughters, and the offspring of her daughters. Among mammal-eating forms, the matriline is also the basic social unit, but the offspring tend to disperse more readily, which results in the smaller average group sizes. It has been suggested that different optimum group sizes have evolved among the different ecotypes to meet the demands of prey specialization (for example, smaller groups are apparently more efficient for hunting small marine mammals), and this has been mediated through varying degrees of dispersal within the matrilineal social structure.

Four basic behavioral modes have been described for killer whales: traveling, feeding, resting, and socializing. Traveling (including foraging) takes up 60%–95% of the activity budget, with fish-eaters spending considerably more time resting and socializing than mammal-eaters.

In Antarctica, the different ecotypes exhibit different foraging behaviors that are also related to prey specialization, although all ecotypes forage cooperatively and any large prey items are usually shared among the group. Small prey is usually swallowed whole underwater; large prey is often brought to the surface and dismembered.

Type A killer whales prey on minke whales up to 9 m in length, and they probably also take calves of larger whales, as well as any sick or injured adults. To kill prey this large requires a coordinated effort by all members in the group, and observations to date suggest that individuals within a particular killer whale group may fill specific roles during these attacks. For example, some individuals stay beneath the prey to prevent it from diving; others may position themselves on the prey's head to prevent it from surfacing and breathing; still others bite down on appendages to slow the animal down and tire it out. To reduce the possibility of injury to the attackers, these attacks often last 2–3 hours, and have been recorded to last more than 7 hours. When killer whales feed on large whales, they prefer the lips and tongues, and when prey is abundant these are often the only parts that they take.

Type B killer whales typically fan out and move through areas of loose pack ice to search for seals hauled out on ice floes. While foraging, members of the group regularly stop and lift their heads vertically out of the water (spyhopping) to visually locate potential prey. Once a seal is detected, the whales have several behaviors for taking it off the ice. If the ice is thin, a whale can crash through from below; if it is thick but small, a single whale can lift up the edge of the floe and spill the seal into the water; for heavier, larger floes, groups have been seen to rush the floe and turn at the last instant, producing a wave that washes the seal into the water.

Little is known about the foraging behavior of Type C killer whales because most of the prey is apparently small enough that it is swallowed whole, underwater. Fish-eating killer whales in Norway are known to herd smaller fish and keep them in a tight ball by swimming around them, releasing bubbles, and slapping their flukes; they then strike the ball with their flukes and feed on the stunned prey.

Young Type C killer whales have been observed herding Adélie penguins *(Pygoscelis adeliae)* in this manner and then letting them go unharmed. It has been suggested that the whales are just "practicing" for feeding on fish schools.

Killer whales, like most delphinids, produce a wide variety of clicks, whistles, and pulsed calls used for echolocation and social signaling. Group-specific dialects are common among the populations studied to date; these appear to reflect relatedness among individuals and groups, and probably assist in maintaining group identity and avoiding inbreeding. Among North Pacific ecotypes, fish-eating forms are much more vocal when traveling and foraging than mammal-eating forms, presumably because all marine mammals have acute underwater hearing and mammal-eating killer whales must therefore hunt silently. These vocalization patterns will likely apply to Antarctic ecotypes also.

Historically, whalers in Antarctica were less interested in taking killer whales (because of their small size), and the catches were generally always small. For example, although the former USSR took 110 killer whales in 1958–1959, they only averaged 24 per season from 1969 to 1978. During the 1979–1980 season, when the International Whaling Commission reduced the allowable Southern Ocean sperm whale catch to zero, the USSR harvested 916 killer whales, which have a somewhat similar oil to that of sperm whales. The following year, the prohibition on whaling in Antarctica was extended to include killer whales and none has been taken (legally) since then.

Antarctica may have the highest density and largest overall population of killer whales of anywhere in the world. Two recent (1990 and 1995) population estimates were 70,000 and 80,400 individuals. These figures, however, do not include a breakdown by ecotype, and they may be underestimates because the ships that did the surveys generally did not venture into the pack ice, where Types B and C killer whales are typically found, often in abundance.

Although whaling is not a current threat to Antarctic killer whale populations, commercial fishing for Antarctic toothfish has recently begun in Antarctica, and this represents an unknown, but potentially important, impact because the fishery targets the only known prey of Type C killer whales.

Robert L. Pitman

See also **Adélie Penguin; Fish: Overview; International Whaling Commission (IWC); Minke Whale (Antarctic Minke Whale); Pack Ice and Fast Ice; Southern Elephant Seal; Toothfish; Whales: Overview; Zooplankton and Krill**

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KING GEORGE ISLAND

Location, General Shape, Topography, and Area

King George Island, South Shetland Islands, is located at 62°05′ S, 58°15′ W and lies 144 km to the southwest of Elephant Island. It is separated from Nelson Island to the southwest by Fildes Strait, a narrow passage about 500 m wide. The island is the largest in the South Shetland group, extending 80 km from east to west and almost 30 km from north to south at its widest point. King George Island has an area of 1260 km^2, of which 98 km^2 are ice free (areas calculated using SCAR 2004); 92.2% of the island is covered by a permanent icecap rising to an elevation of 700 m.

The northern coastline is dominated by ice cliffs, punctuated by several prominent headlands, the easternmost of which is known as North Foreland. This rugged and exposed coastline is peppered with offshore rocks and reefs, and is rarely visited. In contrast, the southern coast is comparatively sheltered, and is indented by four large embayments—Sherratt Bay, King George Bay, Admiralty Bay, and Maxwell

Bay, the last of which is enclosed in part by Nelson Island. Apart from a few nunataks protruding through the icecap, the island's ice-free ground is concentrated in the coastal areas. The geology of the island is covered under this encyclopedia's entry for the South Shetland Islands.

At the southwestern extremity of King George Island lies Fildes Peninsula, one of the most extensive ice-free areas found in the South Shetland Islands. Extending approximately 10 km from north to south and up to 4 km in width, Fildes Peninsula has an area of around 33 km^2. The peninsula consists of a series of low hills and small plateaux rising to elevations of around 100 m, with approximately 40 lakes and more than 20 streams. These are the largest freshwater bodies found on King George Island, and some of the most extensive in the region. The combination of relatively gentle ice-free topography together with a safe harbour in Maxwell Bay with good ship-to-shore access has led to the establishment of four scientific stations on the peninsula. Two further stations are located on Potter Peninsula and Barton Peninsula, which are smaller ice-free areas bordering Maxwell Bay to the west.

Admiralty Bay is the largest natural harbour on the southern coast of the island, with a maximum depth of 520 m and a total area of 122 km^2. The first scientific station on the island was established at Admiralty Bay on Keller Peninsula in 1947 (Base G, UK), and there are currently two year-round and three summer-only stations in this region.

The climate at King George Island is typical of the maritime Antarctic, with high precipitation and cloud cover. Precipitation falls mostly as snow, and is around 400 mm annually (Lindsay 1971). The mean daily air temperature is above 0°C for at least one month during the summer, and the mean for the period from December to March exceeds this figure in some years. In winter, temperatures may drop to a mean daily minimum of around –11°C (Lindsay 1971).

Flora and Fauna

The island's ice-free areas support a vegetation cover consisting of algae, lichens, and bryophytes, together with grass and cushion plant formations. Vegetation communities generally resemble those found on the South Orkney Islands and the Antarctic Peninsula, although bryophytes do not form the deep peat accumulations typically found in the South Orkney Islands. While growth is localised and patchy according to conditions, vegetation stands are comparatively extensive for Antarctica. Rich bryophyte development may be found at sites with moist soils, with the most widespread moss turf communities formed by *Polytrichastrum alpinum* and *Polytrichum piliferum*. Large stands of the moss *Sanionia uncinata* are also commonly found on moist flat ground in coastal areas (Lindsay 1971). There is a much greater development of bryophyte communities on the southern coasts than in the north of the island. Drier slopes often support a dense cover of lichen growth, with fruticose lichens such as *Usnea* species commonly forming associations with moss cushion formations. Crustose lichens such as *Caloplaca* and *Xanthoria* species typically occur on more exposed rock surfaces. The two native vascular plants (*Deschampsia antarctica* and *Colobanthus quitensis*) occur at many of the ice-free sites on the southern coast of the island; however, they are largely absent from the northern coast. The most extensive communities of bryophytes and vascular plants are found in sheltered parts of Admiralty Bay, particularly at Point Thomas (close to Arctowski station) (Lindsay 1971).

The ice-free areas also host large colonies of breeding birds in the summer, with thirteen permanent resident species. Of the three species of penguin represented, the most numerous are the chinstraps, with approximately 300,000 breeding pairs, followed by Adélies with around 55,000 pairs, and lastly the gentoos with approximately 10,000 pairs (Woehler 1993). The largest colonies are located along the exposed and rugged northern coast of the island, where 90% of the local chinstraps breed in 15–20 main colonies. The two largest chinstrap colonies are found at

Breeding Bird Species on King George Island

Common Name	Scientific Name
Adélie penguin	*Pygoscelis adeliae*
Chinstrap penguin	*Pygoscelis papua*
Gentoo penguin	*Pygoscelis antarctica*
Sub-Antarctic skua	*Catharacta [skua] antarctica loennbergi*
South polar skua	*Catharacta [skua] maccormicki*
Southern giant petrel	*Macronectes giganteus*
Cape (pintado) petrel	*Daption capense*
Wilson's storm petrel	*Oceanites oceanicus*
Black-bellied storm petrel	*Fregetta tropica*
Kelp gull	*Larus dominicanus*
Antarctic (blue-eyed) shag	*Phalacrocorax [atriceps] bransfieldensis*
Antarctic tern	*Sterna vittata*
Sheathbill	*Chionis alba*

Pottinger Point (~55,000 pairs) and at False Round Point (~50,000 pairs). The other two resident penguin species breed at ice-free locations on the southern side of the island. This pattern of distribution has been explained by the perennial persistence of early-summer sea ice on the northwestern coast, which impedes access by Adélies to ice-free sites at the time when they commence breeding. They therefore seek out the more accessible sites on the more sheltered and relatively ice-free southern coast, while the later-breeding chinstrap takes up residence in the north once the sea ice has started to recede (Trivelpiece and Fraser 1996).

The largest Adélie colony of ~14,500 pairs is at Stranger Point, while the largest gentoo colony is at Ardley Island with approximately 4500 pairs, both situated in Maxwell Bay. There is evidence that numbers of both chinstrap and Adélie penguins on King George Island have been in decline over the last several decades, while gentoo numbers may have exhibited some increase (Woehler and Croxall 1997). The numbers of all species fluctuate widely interannually.

Approximately 3000 pairs of southern giant petrels *(Macronectes giganteus)* breed around the coast of King George Island (Naveen et al. 2000), with the largest single group of around 630 pairs breeding on Penguin Island on the southern coast. This species is known to be particularly sensitive to human disturbance and local declines in numbers have been reported in several locations close to stations and in areas of high activity (Harris 1991a, 1991b; Pfeiffer and Peter 2004). Approximately 100 pairs of Antarctic shags *(Phalacrocorax [atriceps] bransfieldensis)* breed at Turrett Point near Penguin Island (Naveen 2003), while two small colonies, each of ~10 pairs, breed on the northern coast (Poncet, personal communication, 2004).

Several species of seal are common in the region: elephant seals and Weddell seals are regular breeders, while nonbreeding species include Antarctic fur seals, leopard seals, and crabeater seals, the latter often seen on local ice floes.

Mammal Species Observed on King George Island

Common Name	Scientific Name	Breeding
Antarctic fur seal	*Arctocephalus gazella*	Not significant
Crabeater seal	*Lobodon carcinophaga*	Not significant
Elephant seal	*Mirounga leonina*	Yes
Leopard seal	*Hydrurga leptonyx*	Not significant
Weddell seal	*Leptonychotes weddellii*	Yes

Marine Flora and Fauna

The near-shore marine environment around King George Island is characterised by habitats similar to those found in other parts of the South Shetland Islands. The coastal marine flora and fauna are representative of communities found in the transitional area between the sub-Antarctic and continental zones of the Southern Ocean (ASPA No. 151 management plan). Macroalgae colonise near-shore areas to depths of up to 100 m and are found in diverse assemblages, with common species including *Rhodophyta* and *Phaeophyta*. There is a high abundance and biomass of benthic fauna, with bivalve molluscs such as *Laternula elliptica* and *Mysella charcoti* dominating in numbers in many areas up to around 30 m depth. Amphipods and polychaetes are also major components of benthic faunal abundance (ASPA No. 151 management plan), with polychaetes the most abundant group at increasing depths up to around 250 m. Other vagile and scavenger invertebrates include *Sterechinus neumayeri* (sea urchin) and *Glyptonotus antarcticus* (giant isopod). In deeper waters, sessile organisms such as sponges, anemones, and tunicates are present on stable, muddy substrata (Admiralty Bay ASMA management plan). A total of almost 400 benthic invertebrate species have been recorded in Admiralty Bay. Disturbance from icebergs and anchor ice is a major regulating factor of benthic communities in shallower waters (Sahade et al. 1998).

Thirty-five species of fish have been recorded in Admiralty Bay, the majority of which are *Notothenia* or *Trematomus* species (Skora and Neyelov 1992). Offshore, King George Island is surrounded by productive waters that are important foraging grounds for birds and seals breeding on the island and at other nearby locations. Commercial fishing for Antarctic krill is also conducted in the Drake Passage to the northwest of King George Island (CCAMLR 2005).

Protected Areas

Fildes Peninsula and Ardley Island were originally designated Specially Protected Area (SPA) No. 12 in 1966 on the grounds that they were considered a "biologically diverse region with numerous small lakes which are ice-free in summer, that...provides a representative sample of the South Shetland Islands and is an area of outstanding ecological interest" (ATCM Recommendation IV-12). However, immediately after designation, Bellingshausen Station (Soviet

Union) was established in the central part of the site, which resulted in a decision by the Treaty Parties in 1968 to reduce the area to comprise only a small area surrounding a lake in the northeastern part of the peninsula. This remains the most striking example of disregard for the values of a protected area in Antarctica, and it is perhaps indicative of the politics of the day that the SPA was revoked rather than the station removed. The down-sized SPA was revoked completely in 1975, and today Artigas Station (Uruguay) draws its water supply from the lake. Despite being one of the most populated and heavily impacted parts of Antarctica (Harris 1991a, 1991b; Grant 2006), there remains much of biological and scientific interest. However, to date there is no coordinated framework for environmental management of activities in Maxwell Bay, which is one of the most intensively used locations in Antarctica.

Five terrestrial Antarctic Specially Protected Areas (ASPAs) exist on King George Island, four of which were designated on the grounds that they contain significant colonies of breeding birds and seals, as well as locally rich vegetation: ASPA No. 128, Western Shore of Admiralty Bay (17.5 km^2); ASPA No. 132, Potter Peninsula (1.9 km^2); ASPA No. 150, Ardley Island (1.5 km^2), and ASPA No. 151, Lion's Rump (1.3 km^2). ASPA No. 151 also includes a small marine component (<0.5 km^2). The fifth area (ASPA No. 125, Fildes Peninsula) protects two small sites (total area 1.8 km^2) containing fossil outcrops.

An Antarctic Specially Managed Area (ASMA) for Admiralty Bay was adopted in 1996 for voluntary observance to assist with the coordination of activities and to help protect environmental, scientific, scenic, and historical values in the region. The ASMA covers 370 km^2, and comprises the area within the glacial drainage basin of the bay, together with its entire marine area. The responsibility for coordinating implementation of the ASMA management plan rotates between Poland and Brazil, which operate year-round stations in Admiralty Bay.

Discovery, Exploration, History

King George Island was first recorded on 16 October 1819 by William Smith, who claimed possession for the United Kingdom when he landed near North Foreland and named the island after King George III (Headland and Keage 1985). Smith repeated the possession ceremony at King George Bay on 22 January 1820 on a subsequent voyage accompanied by the British naval captain Edward Bransfield. The first charts of the island were prepared on Smith's early voyages. The following years saw an immediate start to the fur sealing industry in the South Shetland Islands, with up to fifty vessels of mainly British and American operators working at King George Island in the summer of 1820–1821. Smith alone reported taking around 30,000 skins that season (Headland and Keage 1985). The over-exploitation of fur seals led to the collapse of the industry in 1824, by which time local populations were virtually wiped out, and although there were brief resurgences from 1843–1854 and 1871–1880, these only further served to eliminate the species almost completely from the island. The local population at King George Island has never recovered, and numbers today are only a small fraction of what they once must have been. Archaeological evidence of sealing activity such as wrecks, shelter ruins, seal bones, and tools still remains.

The early exploration and charting of the island was thus principally by sealers who kept much of their knowledge secret to protect their commercial interests. However, the island was also charted and named (as Waterloo Island) by the Russian Bellingshausen in January 1821, although he did not land. In the same year, eleven men from the *Lord Melville* (a sealing vessel from London commanded by Clark) became the first party to winter over in Antarctica, doing so at Esther Harbour (Roberts 1958). A range of exploratory expeditions visited and charted King George Island in the following decades. Eduard Dallmann left a copper plaque affixed to a post to commemorate the visit of his German expedition on 1 March 1874 onboard *Grönland,* the first steamship to reach Antarctica. The site is protected as Historic Monument No. 36 under the Antarctic Treaty, although unfortunately this failed to prevent the original plaque from being taken, and it is was replaced by a replica in 1987 (Heap 1990).

The modern whaling industry at King George Island began in 1906, with Admiralty Bay being used as a harbour for whale-catchers and factory ships until 1931. Evidence of the industry remains in the form of whale bones still present on many of the bay's beaches.

The Historic Sites and Monuments on King George Island and their reasons for designation are listed in the following table.

Current Human Activities

The major human activities on King George Island today are science, logistics, and tourism. The island is a popular destination for ship-borne tourism, with

Historic Sites and Monuments on King George Island

Site	Location	Reason for Designation
HSM No. 36	Potter Cove	Metal plaque erected by Eduard Dallmann to commemorate his German expedition of March 1, 1874. Original disappeared; was replaced with replica by Germany in 1987–1988.
HSM No. 50	Fildes Peninsula	Plaque commemorating the first Polish Antarctic Expedition in 1976.
HSM No. 51	Point Thomas	Grave of Wlodzimierz Puchalski, who died January 19, 1979, whilst working at Arctowski Station.
HSM No. 52	Great Wall Station	Monolith to commemorate the establishment of Great Wall Station, February 20, 1985.
HSM No. 53	Presidente Frei Station	Plaque and bust commemorating the rescue of survivors from Shackleton's ship by the Chilean cutter *Yelcho*. A replica of the same monument was erected on Elephant Island.

Scientific Stations on King George Island

					Personnel	
Station	Location	Operator	Established	Status	Capacity	Winter
Artigas	Fildes Peninsula	Uruguay	1985	Year-round	60	9
Bellingshausen	Fildes Peninsula	Russia	1968	Year-round	38	25
Great Wall	Fildes Peninsula	China	1985	Year-round	40	14
Presidente Eduardo Frei Montalva/Teniente Rodolfo Marsh Aerodrome	Fildes Peninsula	Chile	1969/1980	Year-round	150	80
Professor Julio Escudero	Fildes Peninsula	Chile	1994	Summer only	20	-
King Sejong	Barton Peninsula	Republic of Korea	1987	Year-round	60	15
Teniente Jubany	Potter Peninsula	Argentina	1948	Year-round	100	20
Dallmann Laboratory	Potter Peninsula	Germany		Summer only	12	-
Base G	Admiralty Bay	United Kingdom	19471–1961	Removed	-	-
Henryk Arctowski	Admiralty Bay	Poland	1977	Year-round	40	12
Comandante Ferraz	Admiralty Bay	Brazil	1984	Year-round	40	12
Machu Picchu	Admiralty Bay	Peru	1989	Summer only	28	-
Peter J Lenie	Admiralty Bay	United States	1985	Summer only	4	-
Vicente	Admiralty Bay	Ecuador	1988	Summer only	~6	-
Totals					**598**	**187**

large numbers of vessels visiting stations in Admiralty Bay in particular. Fildes Peninsula is also one of the few destinations for tourist flights to Antarctica, with regular short visits originating mainly from Punta Arenas (Chile) during the summer.

There are currently eight year-round scientific stations and five summer-only stations on King George Island, as well as several temporary or permanent field camps and refuges. Twelve countries operate stations on the island (Argentina, Brazil, Chile, China, Ecuador, Germany, Peru, Poland, Republic of Korea, Russia, United States, and Uruguay). Scientific and logistic personnel are present on King George Island year-round, with a winter population of almost 200 and a significant increase in numbers up to a maximum of around 600 in summer.

The first station to be established on King George Island was established in 1947 by the Falkland Islands Dependencies Survey (FIDS, United Kingdom) on Keller Peninsula, Admiralty Bay, and named Base G. Continuous occupation of Base G ceased in 1961. Small huts in Admiralty Bay were also established by Argentina around the same time (and also at Potter Cove), and later by Italy (1976–1977), before the construction by Poland of a year-round station (Henryk Arctowski) at Point Thomas in 1977.

The largest station complex on the island is operated by Chile, and is situated on Fildes Peninsula. Eduardo Frei Montalva station was established in 1969, and is operated year-round by the Fuerza Aréa de Chile (Chilean Air Force). It also contains a small civilian community (Las Estrellas) with its own school, church, hospital, and bank. A gravel airstrip (Teniente Marsh Aerodrome) was built close to Frei station in 1980, and was extended to its current length of 1300 m in 1984. This airstrip is suitable for large, fixed-wing aircraft and is a major hub for transport to and from other stations and field camps in the Antarctic Peninsula region. Professor Julio Escudero station was established beside the Frei complex in 1994 to house scientific personnel, and is operated independently by the Chilean Antarctic Institute. The entire complex is occupied by up to 170 people during the summer.

Located immediately adjacent to the Frei complex, Bellingshausen station was constructed by the Soviet Union in 1968. It was used primarily as a resupply station for the large Soviet fishing fleet operating in the Antarctic Peninsula region until the late 1980s, and remains operational year-round as a scientific station. In 1984, Uruguay established Artigas station on the eastern shore of northern Fildes Peninsula, and in 1985 the Great Wall station was constructed by China, around 0.5 km to the southwest of Frei.

Scientific stations are also located on two further ice-free areas on the southern coast of King George Island, within the Maxwell Bay area. Jubany Station was established by Argentina at Potter Cove (Potter Peninsula) in 1982, built around the huts that had been established at the site by Argentina in 1947–1948, and has since been occupied continuously. In 1994, Germany constructed the neighbouring Dallmann Laboratory, which is occupied by both Argentinean and German scientists and supported by the facilities of Jubany Station. The Republic of Korea established the year-round King Sejong station at Marion Cove (Barton Peninsula) in 1988.

Brazil established its year-round Comandante Ferraz station close to the abandoned Base G in 1984. A summer-only field camp (Peter J. Lenie, also known as "Copacabana") was constructed close to Llano Point within ASPA No. 128 (Western Shore of Admiralty Bay) in 1985, and has since been occupied every summer by scientists studying the surrounding bird colonies. Ecuador also has a small field camp (Vicente) at Hennequin Point, which has been irregularly occupied during summers since 1988, and a summer-only station was constructed by Peru at Crépin Point in 1989.

Key Resources

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See also **Adélie Penguin; Algae; Antarctic Fur Seal; Antarctic Peninsula; Archaeology, Historic; Argentina: Antarctic Program; Bellingshausen, Fabian von; Benthic Communities in the Southern Ocean; Brazil: Antarctic Program; British Antarctic Survey; Chile: Antarctic Program; China: Antarctic Program; Chinstrap Penguin; Crabeater Seal; Dallmann, Eduard; Fish: Overview; Gentoo Penguin; Germany: Antarctic Program; Italy: Antarctic Program; Leopard Seal; Lichens; Molluscs; National Antarctic Research Programs; Poland: Antarctic Program; Protected Areas Within the Antarctic Treaty Area; Russia: Antarctic Program; Russian Naval (*Vostok* and *Mirnyy*) Expedition (1819–1821); Sealing, History of; South Korea: Antarctic Program; South Orkney Islands; South Shetland Islands; South Shetland Islands, Discovery of; Southern Elephant Seal; Southern Giant Petrel; Tourism; United States: Antarctic Program; Weddell Seal; Whaling, History of; Zooplankton and Krill**

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KING PENGUIN

Second largest among the penguins, king penguins *(Aptenodytes patagonicus)* are important in sub-Antarctic latitudes. At 85–95 cm they are only slightly shorter than emperor penguins *(A. forsteri),* but at just 9–17 kg they are half their mass. Their close relationship with emperor penguins is clear from their general body shape, size, and pattern of coloration. Adult king penguins are easily distinguished, however, by their thinner body, relatively long bill, and deep orange auricular patches in a characteristic inverted-teardrop shape on either side of the head. The corresponding patches on emperor penguins are more oval in shape and yellow in color. Immature members of both species have paler colors, but the longer bill and teardrop-shaped auricular patches are still characteristic of king penguins. The genders are alike in coloration, but males are slightly larger than females.

There is continuing argument over the number and taxonomy of several penguin species, but the king penguin is clearly distinct. The latest taxonomy places the king and emperor penguins with the brush-tailed *(Pygoscelis),* crested *(Eudyptes),* and yellow-eyed *(Magadyptes)* penguins. Together, these four genera appear to have split off from the striped *(Spheniscus)* and little *(Eudyptula)* penguins early in their evolution.

King penguins currently breed at nine islands in the sub-Antarctic that are scattered around the south Atlantic and Indian oceans: Macquarie, Heard, Kerguelen, Crozet, Prince Edward, Marion, South Sandwich (few), South Georgia, and the Falklands (small population). Formerly, they also bred on Staten Island and parts of Tierra del Fuego. They are absent from the south Pacific between Tierra del Fuego and New Zealand, but forage throughout the rest of the sub-Antarctic waters of the southern ocean. Two subspecies are currently recognized, *A. p. patagonicus* at South Georgia and the Falklands and *A.p. halli* everywhere else. The situation may be more complex, however, because there is considerable body-size variation at different islands and there is good evidence that the populations on Kerguelen and Crozet are genetically isolated from each other.

King penguins are unique among the penguins in that they do not breed annually. In fact, at c. 400 days, king penguins have the longest nesting cycle of any seabird. There is also more variation in the schedule of breeding than other penguin species. Some populations try to breed every other year (e.g., Crozet and Possession Islands) and other populations are able to succeed twice in 3 years (e.g., South Georgia). This variation results in birds' being present and breeding at king penguin colonies year round. A single colony may have different adults incubating eggs, performing courtship, feeding large chicks, and moulting all present simultaneously.

Typically the breeding cycle begins (i.e., year 1) with courtship in the spring. Unattached birds use upright postures and calls to advertise for mates. A bird will stand erect with the head horizontal and flippers held close to the body, then raise the head to point at the sky, extend the neck, and call. The calls use two frequency bands simultaneously so they have internal harmonics. They sound somewhat like a trumpeting elephant. Calls are important during courtship to advertise for mates, but they are also used to locate and identify mates and chicks.

Once the pair is established and mated, the female lays a single egg in late November. She holds the egg on her feet and covers it with a loose flap of skin on the lower abdomen. There are no nests constructed. She will incubate the egg for a few hours then pass it to the male. After that, they will alternate incubating the egg and foraging in 4 further shifts of 12–18 days. The males and females split the duties of incubation. When the egg hatches after 54 days, the pair alternates brooding/feeding the chick and foraging with 1 adult guarding the chick at all times.

After 31 days, the adults leave their chick behind at the colony and bring food every 5–7 days for another 5–7 weeks. It is at this point that king penguins vary from other penguin species. The combined efforts of courtship, incubation, and brooding take so long that the chick is not ready to fledge by the time the weather and sea conditions begin to deteriorate in March and April. The parents have fed their chicks to c. 12 kg (nearly adult size) but it is too late for the chicks to moult and learn how to forage on their own. The adults then abandon the chicks for a variable period that ranges from a couple of weeks to a few months depending on conditions and colony. The chicks may lose a third of their body mass before the adults return and resume feeding them for another two months.

When the chick fledges in October or November, the adults moult, then begin the breeding process anew. This time the egg will be laid in February and the entire process gets shifted in the year. By the time this chick fledges, it will be the end of summer in year 3. Now the adults will be back on track to start over at the beginning of year 4. The adults are flexible to the point that if they lose an egg or chick early in the spring then they will start again in late summer. Or if they lose a chick in late summer, fall, or winter, they will reset their schedule at year 1 and begin again in October. Consequently, the best they can do is two chicks every 3 or 4 years, depending on their colony. This complex and variable breeding schedule and the lack of a physical nest site are why king penguins have very low pair fidelity with a 71% divorce rate between years.

Newly hatched chicks are brown and nearly naked of feathers. They quickly develop their first light brown down coat. By the time they go to the crèche, their downy coat is long and rich brown, unlike any other penguin. By the time they fledge, they moult into immature plumage with little or no orange and yellow pigments so they look like faded adults. Immature king penguins moult into their full adult colors at the beginning of their third year. A few of those 3-year-olds will attempt to breed, but normally they will be 4 or older before they start to breed.

King penguins primarily eat fish during the breeding season, but squid are much more important in the winter. While they are feeding a chick at the colony, king penguins rarely travel more than 300 km from their colony, but travel much farther during the winter months. They are capable of diving to over 300 m. Their foraging trips are regularly longer than 4 or 5 days and king penguins have developed a remarkable physiological adaptation. Using antibiotic enzymes in their intestinal tract, they are able to preserve partially digested food so bacteria do not spoil the partially digested fish and squid that they are taking back to their chicks.

Eggs and small chicks are preyed on by skuas (*Catharacta* spp.), giant petrels (*Macronectes* spp.), and sheathbills (*Chionis* spp.), though most of their opportunities come from scavenging abandoned eggs and chicks. As the king penguin chicks grow, they quickly become too large for all predators except giant petrels. Adults are essentially free from predators on shore, but are killed by leopard seals *(Hydrurga leptonyx)* and orcas *(Orcinus orca)* at sea.

King penguins were commercially hunted as a source of oil in the nineteenth and twentieth centuries. They were exterminated from Tierra del Fuego and the Falkland Islands (c. 1870), and some colonies were destroyed on Macquarie Island and at South Georgia. Since that persecution stopped, they have recolonized Heard Island and the Falkland Islands and the populations worldwide have been growing. Estimates of the worldwide population range from 1.6–2.2 million breeding pairs—their unusual breeding schedule make them notoriously difficult to estimate. King penguin populations are currently not threatened directly, but there is some concern for indirect competition with commercial fisheries in some of their range.

Gary D. Miller

See also **Crested Penguins; Crozet Islands (Îles Crozet); Emperor Penguin; Fish: Overview; Heard Island and McDonald Islands; Kerguelen Islands (Îles Kerguelen); Leopard Seal; Macquarie Island; Penguins: Overview; Prince Edward Islands; Sheathbills; Skuas: Overview; South Georgia; South Sandwich Islands; Southern Giant Petrel; Squid**

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LAKE ELLSWORTH

From the various subglacial lakes identified thus far in Antarctica, subglacial Lake Ellsworth stands out as a suitable candidate for *in situ* measurement and sampling. Located at 79.0° S, 90.5° W in West Antarctica, only ~20 km from the ice divide, the lake has been measured by the radio-echo sounding technique to be about 10 km in length. Ice thickness over the lake is around 3.4 km and, like that of Lake Vostok, the lake's ceiling has a noticeable slope (by around 200 m over its entire length), which may drive water flows within the lake. Modeling of the ice-sheet thermal regime shows that, with a background level of geothermal heating, the ice sheet above Lake Ellsworth is expected to be warm-based both now and during full glacial periods. As the lake occupies a distinct deep topographic hollow, it is likely that it will have remained in place even if the ice sheet topography has changed (water in lakes not bounded by significant relief may, however, "outburst" as a consequence of such change). The age of Lake Ellsworth is, therefore, likely to be as old as the ice sheet itself. The age of the West Antarctic ice sheet is, however, not known. It is probably much less old than the 15 million years of East Antarctica, and could be as young as a few hundred thousand years. The age of the lake's water is dictated by the age of ice that melts into the lake, which in West Antarctica should be around 150,000 years or so.

Despite its being younger than many subglacial lakes, the boundary conditions of Lake Ellsworth will be much of the same as any other lake, making it appropriate for exploration as an analogue to others. Given that the base of the West Antarctic ice sheet has been accessed on several occasions, there is precedent for *in situ* exploration of Lake Ellsworth. This may make environmental issues concerning lake access easier to overcome in Lake Ellsworth than in East Antarctic subglacial lakes, where the ice sheet base has never been reached.

MARTIN J. SIEGERT

See also **Antarctic Ice Sheet: Definitions and Description; CryoSat; Glaciers and Ice Streams; Ice–Rock Interface; Ice Sheet Mass Balance; ICESat; Lake Vostok; Subglacial Lakes**

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Subglacial Antarctic Lake Exploration (SALE) group of specialists. http://salegos-scar.montana.edu/

LAKE VOSTOK

Subglacial Lake Vostok, being over 250 km in length and 80 km wide, is by far the largest subglacial lake in Antarctica. It was discovered in the 1970s using a technique called radio-echo sounding (RES). Scientists did not appreciate either the full extent of the lake or that the Russian base Vostok Station was located over its southern end until satellite altimetry of the ice-sheet surface, during the early 1990s, revealed an unusually flat region above the lake (caused by the change in flow dynamics as ice moves from being grounded on rock to floating in the lake water). As a consequence, seismic data acquired at Vostok Station in the 1960s were reinspected to reveal the depth of the lake's water column to be 510 m. Since about 1996, additional RES data have been obtained over Lake Vostok. These data show that the ice thickness over the lake increases steadily from 3750 m in the south to 4200 m in the north of the lake. As the ice-sheet surface varies by only 50 m or so, this thickness change manifests itself as a sloping lake ceiling. The rate of subglacial melting and freezing will vary in relation to this slope; melting will occur where the ice is thickest, and freezing will take place at the southern end where the ice is thinner. This pattern of melting and freezing has been confirmed by both RES studies of the lake-water interface and the Vostok Ice Core, which has sampled around 60 m of refrozen lake ice from its base. Subglacial melting and freezing above Lake Vostok will lead to heat exchange between the ice and lake, and flow of lake water. Although the mean speed of water flow has been modeled numerically to be on the order of 1/10th of a millimeter per second, the Coriolis force (due to the spinning of the Earth) may result in ascending/descending plumes of water with a greater flow speed. Airborne gravity measurements over Lake Vostok reveal the lake cavity to consist of two basins. Direct measurements of lake's bathymetry are only possible, however, using seismic surveying, which has yet to be applied fully to this environment.

Lake Vostok has received world-wide scientific and media coverage as an extreme habitat in which unique microorganisms may exist. Over the past 10 years, there have been several conferences dedicated to understanding how this lake may one day be explored. Many glaciologists believe, however, that alternative subglacial lakes, such as Lake Ellsworth in West Antarctica, may be better suited for exploration, at least in the first instance.

Critical to the nature of the inhabitants of Lake Vostok will be its age and origin. The lake is likely to be as old as the ice sheet itself, which some scientists believe is around 15 million years in East Antarctica. The age of the lake's water, however, will simply be as old as the ice that melts into it, which for Lake Vostok is around 1 million years. The origin of Lake Vostok has received considerable debate in the recent literature. Airborne geophysics reveals a preglacial geological fault along the lake's long axis. Lake Vostok may, therefore, be located within a trough that predates the ice sheet. However, the extent to which glacial erosion may have subsequently contributed to the excavation of the lake's cavity remains unknown.

MARTIN J. SIEGERT

See also **Antarctic Ice Sheet: Definitions and Description; CryoSat; Glaciers and Ice Streams; Ice–Rock Interface; Ice Sheet Mass Balance; ICESat; Lake Ellsworth; Subglacial Lakes**

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LAMBERT GLACIER/AMERY ICE SHELF

A drainage basin is defined as the topographic land area that contributes material flow to a common outlet region or point. In Antarctica the catchment input is snow, and the output glacial ice. The ice flows slowly at first from the high inland divides and summit domes, before gradually gaining pace as it funnels into individual glaciers and ice streams. Glaciers exhibit channel flow in well-defined bedrock valleys or depressions, whilst ice streams are currents of ice in the ice sheet that flow faster than the surrounding ice (often on a deformable bed).

The Lambert Glacier drainage basin occupies an area of 1.5 million km^2, comprising some 16% of the total area of East Antarctica. Its southernmost point is Dome Argus (81° S, 77° E), high on the Polar Plateau at an elevation of approximately 4040 m. The basin annually drains some 35–40 billion tonnes of ice per year via a number of outlet glaciers through the Prince Charles Mountains into the Amery Ice Shelf, which itself contains 71,000 km^2 of floating ice. This system, the largest in East Antarctica, has a highly convergent flow pattern, with mass discharge focussed through the front of the Amery Ice Shelf, which accounts for less than 3% of the East Antarctic coastline.

The Lambert Glacier is one of the largest in the world, measuring 800 km in length by 32 km wide in places. Ice thickness reaches 3500 m deep in a bedrock trough along the eastern edge of the graben (geological subsidence fault) in which the glacier flows. Surface speeds there are as little as 60 m/yr, and even lower deep inland, but approach 900 m/yr near where the glacier crosses the grounding zone (where it starts to float and become an ice shelf), at the confluence of several major outlet glaciers (Lambert, Mellor, Collins, and Fisher) west of the Mawson Escarpment at 73.3° S.

Ice thickness on the Amery Ice Shelf reaches 2800 m near the grounding zone, reducing to less than 300 m some 650 km to the north, along the 200-km-wide iceberg calving front in Prydz Bay. Over the northern half of the Amery, much of the thickness reduction is a consequence of thinning and spreading, without change to total ice volume, as the embayment containing it widens out into the open ocean. In the south, however, almost half the initial ice volume is lost due to extensive basal melting that dramatically thins the shelf in the first 120 km after becoming afloat, through contact with the relatively warm ocean waters circulating in the cavity beneath it. Although the ocean water has a mean temperature of only –2°C, it is still several degrees above the local freezing point at the great depths of the ice shelf keel, due to the pressure dependence of the freezing point.

The resulting cool fresher meltwater flows northward along the upward sloping base of the shelf. As it does, frazil (fine spicules or plates of ice) crystals form within the rising plume, because the freezing point increases with the reduction in pressure at shallower depths. These frazil crystals accumulate in pockets or indentations in the base of the shelf, where they compact and consolidate into what is called marine ice (dark green or jade icebergs are a result of this ice). The total amount of accreted marine ice is thought to comprise roughly half that lost through basal melting near the grounding zone, the remainder modifying properties of water masses later emerging from beneath the shelf with reduced salinity chiefly on the western side. Under the Amery, marine ice forms essentially in two longitudinal bands (where different ice streams merge) along the northwestern and north-central sections of the shelf. The layer can be more than 200 m thick, making up more than 40% of the total ice thickness in places. Production of marine ice effectively transfers mass from the thickest parts of the shelf near the grounding zone, to thinner sections toward the front, possibly increasing overall stability of the system.

The southern portion of the Amery has a bare ice surface ablation zone, with sinuous melt streams and shallow lakes often dominating the surface in summer. The northern shelf is subject to incursion of synoptic weather systems, bringing precipitation across the coast producing an overall snow accumulation zone. Parts of the northern Amery thus exhibit a three-layer vertical structure: local snowfall, continental ice from the interior basin, and marine ice accreted to the base at depth.

Iceberg calving is the other principal source of mass loss from the ice shelf. Flow speed at the central calving front is close to 1200 m/yr, but overall ice shelf advance is perhaps only 85%–90% of this, as small chunks of ice shed intermittently throughout the year. Major calving events, producing large icebergs with linear dimensions greater than 25–30 km, tend to be episodic in nature, as is the case for most large ice shelves. The last such breakout for the Amery occurred in the early 1960s, whilst the development of several long rifts currently projecting back from the front suggest that a major calving is imminent, and that periodicity for the Amery is on the order of 40–50 years. These events are natural cycles resulting from weakening of the ice shelf as it slowly spreads and thins further into Prydz Bay through time.

Mike Craven

See also **Antarctic: Definitions and Boundaries; Antarctic Ice Sheet: Definitions and Description; Climate Change; Coastal Ocean Currents; CryoSat; East Antarctic Continental Margin, Oceanography of; Eddies in the Southern Ocean; Firn Compaction; Glaciers and Ice Streams; Ice Sheet Mass Balance; Ice Shelves; Icebergs; ICESat; RADARSAT Antarctic Mapping Project; Remote Sensing; Ross Ice Shelf; Sea Ice: Crystal Texture and Microstructure; Southern Ocean; Southern Ocean: Climate Change and Variability; Synoptic-Scale Weather Systems, Fronts and Jets**

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LARSEN, CARL ANTON

Carl Anton (C. A.) Larsen (August 7, 1860–December 8, 1924) was a sea captain, whaler, and leader of several expeditions to Antarctica that resulted in geographical and scientific discoveries. He started so-called modern whaling in Antarctic waters, and thus led the way for the foundation of that industry.

Larsen was the son of a sea captain from outside Larvik, a port town in southern Norway. He went to sea as a young boy, and sailed on vessels chasing small bottlenose whales in the North Sea. This was an expanding industry at the time. Larsen was given the command of a bottlenose whaling vessel owned by Christen Christensen from nearby Sandefjord. Their association would become important for the future development of the whaling industry.

In the 1880s modern whaling was developing along the shores of northern Norway. The whalers had become able to chase the large, fast-swimming rorquals (blue whales, fin whales, humpback whales) with new powerful technology. It was also discussed in Norway and several other countries at the time to search for new whaling grounds in Antarctica. In the southern summer of 1892–1893, three expeditions went south. One Norwegian expedition was organized by Christen Christensen, who had the idea, the capital, and a vessel, *Jason,* a former sealer. Larsen was hired as the captain and expedition leader.

The expedition in *Jason* caught no whales, but observed them in abundance. The expedition was also of some significance in terms of scientific discoveries. It sailed south in the western parts of the Weddell Sea, and discovered petrified wood (fossils) at Seymour Island, which attracted scholarly attention. After returning to Norway, Larsen and *Jason* immediately returned south for a second season (1893–1894), this time accompanied by two more vessels, *Castor* and *Hertha*. *Jason* sailed back into the Weddell Sea, where it made new geographical discoveries and worked its way through the ice farther south than any vessel had been before in this area of Antarctica (68°10′). The ships also visited South Georgia. After returning home, Larsen put forward the idea of starting a whaling operation there.

Larsen did not immediately proceed with his southern whaling plans. Instead he worked as a manager at a Finnmark (northern Norway) shore whaling station in the late 1890s, and gained valuable experience regarding how modern whaling was organized according to the way Svend Foyn had built up his business.

In 1901 Larsen again travelled to Antarctica, this time as the captain of *Antarctic,* the vessel of the first Swedish South Polar Expedition. This expedition carried out an extensive scientific program along the Antarctic Peninsula, the Falkland Islands, and Tierra del Fuego in South America. *Antarctic* also stayed in South Georgia waters in 1902, and Larsen's plans to start whaling there gradually materialized. The expedition ended dramatically in February 1903 when the *Antarctic* was crushed by the ice and sank in the Weddell Sea, east of Paulet Island, on its way to pick up a shore party at Snow Hill Island farther south. Before the ship entered the ice, another shore party had been left at Hope Bay on the northern tip of the Peninsula, so the expedition members—without a vessel—were spread across three different locations where they had to winter. After an epic tale of survival, the scientists and sailors were rescued by an Argentine vessel in November of 1903 and brought to Buenos Aires.

The short stay in the Argentine capital was of great significance for Larsen. He presented his idea about South Georgia whaling to the local business community, and suggested the founding of a company and setup of a shore whaling station at the island in the sheltered harbour of Grytviken. He quickly received backing, and the name of the new company became Compañia Argentina de Pesca. Larsen returned to Norway, but went to South Georgia again in the autumn of 1904 with three vessels (a steam catcher boat and two transport vessels), crew, and equipment to erect a shore plant. This marks the beginning of modern whaling in Antarctica.

At South Georgia, five more stations were built in the years before World War I. The companies were of different nationalities, but the majority of the whalers came from Norway.

Larsen organized his South Georgia enterprise the way it had been done in Finnmark: setting up a shore station. His former associate, Christen Christensen, started whaling in 1905 with a floating factory ship operating together with steam catcher boats farther south in the South Shetlands. Together with South Georgia, this became the major whaling ground for years to come.

Larsen managed the Grytviken station until 1914. He extended the plant and even built a church for the whalers (1913). In his last years at South Georgia, he considered plans for whaling in other areas, but instead returned to Norway and his home outside Oslo. He bought two large inland farms and planned to develop them into model breeding farms. The project was of limited success, and once more he turned his attention to Antarctica and whaling.

It was well known that there were large numbers of whales in the Ross Sea, and in 1922 Larsen cofounded a company to pursue whaling there. In 1923 the factory ship *Sir James Clark Ross* steamed south together with catcher boats and Larsen as the expedition leader. They worked their way through the ice into the open waters of the Ross Sea. The whaling was a success, and the expedition proved that modern whaling could be undertaken independently from shore bases. It led the way for the next big expansion of the Antarctic whaling industry, the pelagic whaling.

Larsen was back in the Ross Sea the next season. For some time, his health had been failing, and he died on the whaling ground in December 1924.

Larsen was a pioneer whaler, both by transferring whaling from shore stations from north to south, and by venturing into the Ross Sea. He was also one of the most remarkable expedition leaders of the Heroic Age of Antarctic exploration around the turn of the century. His skills as a captain in the rough Antarctic waters were well known and highly respected. Throughout his career, Larsen also took much more of an interest in the scientific part of his expeditions than what would normally have been expected of a sailor.

BJØRN L. BASBERG

See also **Dundee Whaling Expedition (1892–1893); Foyn, Svend; Norwegian *(Tønsberg)* Whaling Expedition (1893–1895); Sealing, History of; South Georgia; Swedish South Polar Expedition (1901–1904); Swedish South Polar Expedition, Relief Expeditions; Whaling, History of**

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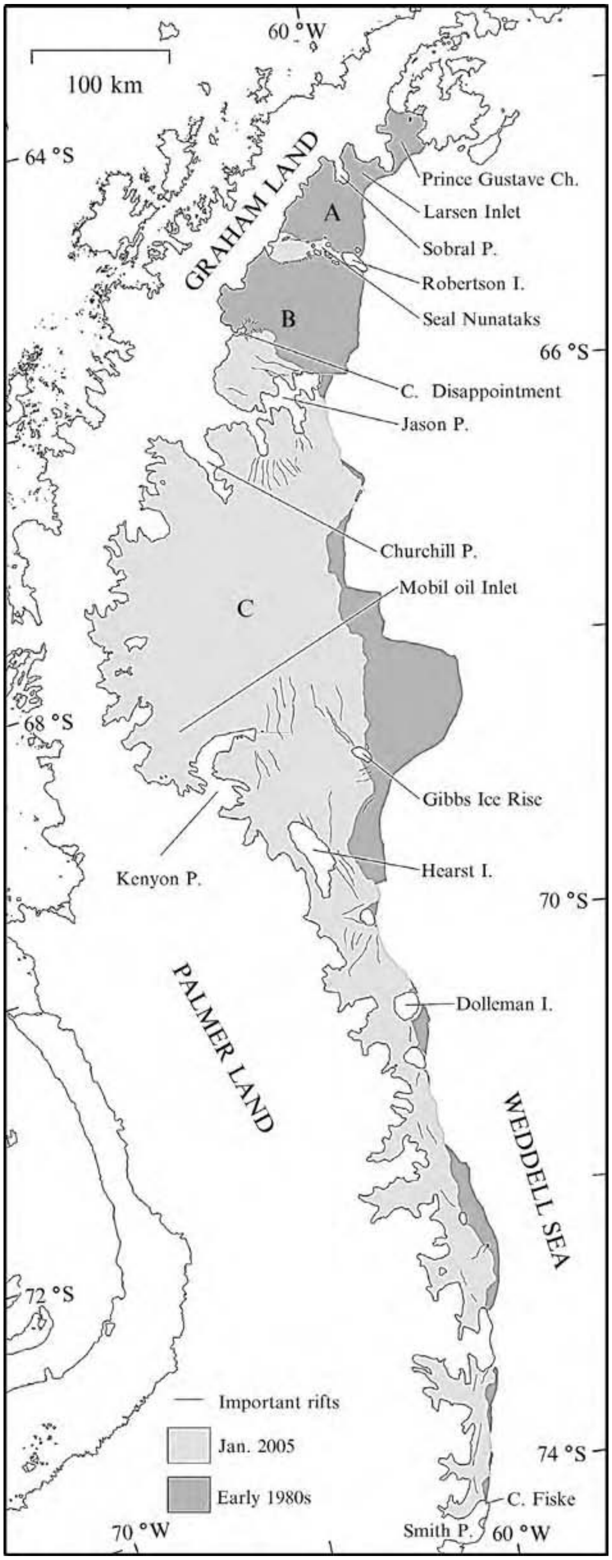
LARSEN ICE SHELF

The Larsen Ice Shelf (68° S, 63° W) fringes the eastern coast of the Antarctic Peninsula. It was discovered in December 1893 by Carl A. Larsen, leader of the Norwegian (Sandefjord) Whaling Expedition (1892–1894), and first traversed in October 1902 by Otto Nordenskjöld, Lieutenant José María Sobral, and seaman Ole Jonasen, members of the Swedish South Polar Expedition (1901–1904).

Until the late 1980s the Larsen Ice Shelf extended from Prince Gustav Channel (64° S) to Cape Fiske (74°15′ S), at Smith Peninsula, covering approximately 103,400 km^2. Five major sectors were distinguished: the portion at Prince Gustav Channel; that between Sobral Peninsula and Robertson Island; the portion between Robertson Island and Jason Peninsula; that between Jason Peninsula and Gibbs Ice Rise; and the one between Gibbs Ice Rise and Cape Fiske. The last four are usually referred to as Larsen A, B, C, and D, respectively. In addition, the portions at Larsen Inlet and between Seal Nunataks are usually treated separately. Documented frontal variations of the northernmost sectors date back to the mid-1940s. In general, the sector at Prince Gustav Channel retreated, whereas Larsen A and B advanced until 1975 and 1995, respectively. Dramatic changes have occurred since the late 1980s. Larsen Inlet disintegrated between 1989 and 1992. Larsen A and the sector at Prince Gustav Channel disintegrated in a few weeks in January–February 1995. In February–March 2002, the portion of Larsen B north of Cape Disappointment disintegrated following an almost identical pattern. In January 2005, as a consequence of these losses and iceberg calving, the area of Larsen Ice Shelf was approximately 78,515 km^2, implying a reduction of 24% since the early 1980s.

On average the ice shelf surface rises 34 m above sea level (asl). It is highest (about 70 m asl) at the grounding line, where the ice sheet starts to float and becomes an ice shelf, and lowest (30 m) at the frontal ice cliffs in the Weddell Sea. The average ice thickness is 240 m, with a maximum of 750 m at Mobil Oil Inlet, and a minimum of about 160 m (and locally less) at Seal Nunataks.

A variety of surface features are observed, especially on Larsen C, but most of them are best appreciated in satellite images because of their low amplitude and large extension. Flow stripes forming at the mouth of tributary glaciers are ubiquitous. These can be traced from the grounding line to the front, delineating ice pathways. Pressure waves appear down ice from lateral topographic obstructions, being especially conspicuous south of Churchill Peninsula and north of Kenyon Peninsula. Rifts, crevasses cutting the entire thickness of the ice shelf, are well developed south of Jason Peninsula and east of Kenyon Peninsula, in Larsen C, and between Hearst and Dolleman islands, in Larsen D. Another rift was located at the limit between Larsen B and the portion between Seal Nunataks. Under normal conditions rifts are present near the ice front and margins, due to extensional opening of fractures. In Larsen A and B, however, ubiquitous rifting developed just prior to the collapses and marked the initiation of these events. Meltwater ponds, sometimes connected by meltwater streams, form in the northernmost sections during warm summers due to large ablation rates. Ice dolines, rounded depressions 0.1–1 km in diameter and 10–20 m in



Larsen Ice Shelf.

depth, are uncommon features that appeared on Larsen A and B in the years prior to their collapses. It is hypothesized that they form due to intense melting and percolation, being considered a sign of ice shelf instability. Minor debris bands are observed on the portion at Seal Nunataks and southeast of Jason Peninsula.

The mass balance of the upper surfaces (ice-air) of Larsen A and B and the portion at Seal Nunataks is known through measurements performed between the early 1980s and 2001. These measurements indicate that the mass balances of Larsen A and the section at Seal Nunataks decreased steadily beginning in the late 1980s and became negative in the beginning of the 1990s. The northernmost part of Larsen B followed a similar pattern, but the balance became negative in the mid-1990s. The southern part of Larsen B, including the surviving portion, also had a decreased balance but it remained positive during the observation period. The mass balance of the lower surface (ice-ocean) has not been measured, but calculations suggest that net melting dominated during the last decade. Recent estimates, supported by field and satellite measurements, indicate that the resulting effect of the negative mass balances on both surfaces during the last decades was a net thinning of the ice shelf.

Ice velocities in Larsen Ice Shelf are in the range of 10–30 m per year in the section at Seal Nunataks to almost 600 m per year at the centre of Larsen C, largely reflecting the rates of ice input from the tributary glaciers. Significant (up to 26%) increases in ice velocity were measured on both Larsen A and B in the years prior to their collapses.

The partial loss of Larsen and other ice shelves in the Antarctic Peninsula region, observed since the late 1980s, is an important environmental issue for the Antarctic. A regional atmospheric warming of 2.5°C measured since the 1940s, in synergy with a 0.32°C warming of the Weddell Sea since the 1970s, appears to be the most likely cause. It is thought that the Larsen Ice Shelf became progressively weakened by the percolation and in-depth refreezing of meltwater produced during warmer summers. Additionally, increased basal melting, resulting from a warmer sea, might have simultaneously thinned the ice shelf, further increasing its exposure to crevasse fracture. The disintegration of ice shelves has no direct effect on sea level. However, the collapse of Larsen Ice Shelf triggered the acceleration of some of its former tributary glaciers. The increased ice discharge, which is not counterbalanced by an increased snow accumulation, is actually contributing to sea level rise.

HERNÁN DE ANGELIS

See also **Antarctic Ice Sheet: Definitions and Description; Antarctic Peninsula; Antarctic Peninsula, Glaciology of; CryoSat; Glaciers and Ice Streams; Icebergs;**

ICESat; Ice Sheet Mass Balance; Ice Shelves; Larsen, Carl Anton; Nordenskjöld, Otto; RADARSAT Antarctic Mapping Project; Remote Sensing; Swedish South Polar Expedition (1901–1904); Weddell Sea

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LARVAE

The life history of most marine invertebrates includes the spawning of gametes followed by the development of a free-living larval stage, which can survive by feeding on phytoplankton or on their yolk supply. In some species the embryos are carried by their parents and released later as either larvae or juveniles. Larvae are in general very different from the adult form and must undergo a metamorphosis to resemble the juvenile or adult body plan. Benthic marine invertebrates in shallow warm water usually generate free-swimming planktonic larvae throughout the year. On the other hand, it has been suggested that polar and deep-sea benthic species generally brood their larvae to protect them from the harsh conditions (Thorson's rule). In polar areas, reproduction and release of juveniles or larvae are also closely related to food availability and to the seasonality of primary production. However, since the 1990s, studies in coastal areas, in bays, and under sea ice have revealed planktonic larvae of an increasing number of Antarctic taxa.

Planktonic development seasonally supplies the Antarctic pelagic food chains with a mass of additional organisms, in some locations mainly due to just one larva morphotype. Many of the individually most successful species in shallow water, such as the sea urchin *Sterechinus neumayeri,* the gastropod *Nacella concinna,* and the nemertean *Parbolasia corrugatus* have planktonic larvae. The ecological dominance of these species with planktotrophic development could be related to the capacity of their larvae to recolonise highly disturbed shallow habitats.

Current estimates of larval abundance in the maritime Antarctic range from 100 to 1600 ind·100 m^{-3}. The major variability in larvae numbers in Antarctic coastal waters has been attributed to seasonality rather than to site or depth. In the shallow waters of Admiralty Bay (King George Island), the succession of invertebrate larvae according to seasonality seems to have been similar for many years, indicating the maintenance of adult reproductive strategies over time. In terms of larval numbers, gastropod veligers can be locally dominant, particularly in mild environmental conditions and higher phytoplankton concentrations. The occurrence of nemerteans and echinoderms has been associated with the onset of summer and high solar radiation levels, whilst different polychaete larvae morphotypes seem to be present throughout summer and during early winter. Bivalve and nudibranch veligers, trochophores, sipunculan pelagosphera, holothurian pentaculae, echinoplutei, ophioplutei, Ascidian tadpoles, cirripedes, bryozoan coronate, and cnidarian planulae have all been recorded in Antarctica.

The coastal Antarctic areas are a source of undiscovered larval biodiversity and the latest studies are trying to identify larvae at low taxonomic levels (i.e., to species), using modern molecular techniques.

The seasonal occurrence of invertebrate larvae may reflect and indicate changes in the ecosystem, including global warming, since reproductive cycles and larval survival are likely to change as a consequence of (seasonally and regionally) rising sea temperature. Planktonic development favours wider dispersal of larvae and establishes connections between the marine populations that are linked by the exchange of larvae. Furthermore, the structure of benthic communities is determined by the supply of recruits, including larval transport mechanisms, settlement success, and post-larval processes. Particular oceanographic conditions, promoted by strong Antarctic katabatic winds, can also control pelagic–benthic coupling and the spatial distribution of larvae. The dynamics of larval movements are critical to the design of conservation units and managements strategies in Antarctica.

Andrea S. Freire

See also **Benthic Communities in the Southern Ocean; Food Web, Marine; King George Island; Molluscs; Pelagic Communities of the Southern Ocean; Reproduction; Wind**

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LAW, PHILLIP

Phillip Law has had a varied career: teacher, scientist, Antarctic explorer, and educational administrator. He is famous mainly for his 19 years of Antarctic work, as the leader of the expeditions that established Australia's permanent presence in Antarctica and explored the major portion of the coast of Australian Antarctic Territory.

Phillip Garth Law was born on April 21, 1912 at Tallangatta, Victoria, the son of a school teacher. He was educated at a country high school at Hamilton, Victoria, and proceeded to Ballarat Teachers College. From this he gained a 1-year scholarship to commence a science degree at Melbourne University. Following that year he taught at secondary schools in the country and in Melbourne, continuing his university studies on a part-time basis. In 1939 he graduated BSc with first-class honours in physics.

Throughout his life, Law participated vigorously in a wide variety of sports, including winning the Australia Universities' Lightweight Boxing Championship at Brisbane in 1936. His mountaineering and skiing activities formed a useful basis for his Antarctic work.

In 1939 he took 2 years' leave from the Education Department to undertake an MSc in physics at Melbourne University. When war broke out later that year, he became a research physicist working on optical instruments for the Scientific Instruments and Optical Panel of the Ministry of Munitions. For this, he was despatched to battle fronts in New Guinea to report on the conditions of gun sights, range-finders, and other optical instruments. At the end of the war, he resigned from the Education Department to become a lecturer in physics at Melbourne University.

In 1947 the Australian Commonwealth government planned an exploratory voyage to Antarctica during the southern summer of 1947–1948. Law heard about it from his professor, applied, and was appointed as senior scientific officer for what became known as the Australian National Antarctic Research Expeditions (ANARE). The project was to locate possible sites for permanent stations that the government could operate. However, the only ice-strengthened ship available was *Wyatt Earp,* a converted fishing ship, used by Lincoln Ellsworth as base ship for his pioneer flights across Antarctica in the 1930s. In 1948, sea ice was very heavy, and the expedition was unable to land on the continent.

Law installed on the ship a set of equipment to record the intensity of cosmic radiation in the atmosphere. This was a program being run by the Melbourne University Physics Department. Law succeeded in operating (and repairing) the equipment, investigating the variations in cosmic-ray intensity with latitude. Later during 1948 he was able to continue these measures on an Australian troop ship on a voyage from Australia to Japan.

During the southern summer of 1947–1948, teams were also recruited and sent to install stations on Heard and Macquarie islands, two sub-Antarctic islands in the Southern Ocean. A former army ship, HMALST 3501, was used to transport them there. The teams stayed at these stations for 1948 and ran weather and upper-atmosphere observations and did some mapping.

In January 1949, the Commonwealth created an administrative office—the Antarctic Division, later titled Australian Antarctic Division (AAD)—and appointed Law its first director. The government's objectives were to operate stations in Antarctica to support Australia's claims there and to run scientific research. This was not possible initially, as no ice-strengthened ship was available. So for the first 4 years in his position, Law built up his headquarters staff, developed administrative procedures, and set up science research programs on Heard and Macquarie islands. He brought in other government departments and universities with science and technology specialisations to collaborate in setting up research programs and to provide some personnel.

Law sailed to the island stations each summer on the HMALST 3501 (later renamed HMAS *Labuan*). The new teams took over the stations, new buildings and equipment were installed, and new scientific research programs started. Law also sailed on the Norwegian-British-Swedish Antarctic Expedition vessel MV *Norsel* to Dronning Maud Land in summer 1949–1950, to observe at first hand their operations.

In 1953 a Danish polar ship, *Kista Dan* of the J. Lauritzen Company, was launched and Law chartered it for summer 1953–1954. He chose a location at the western end of Australian Antarctica, in Mac. Robertson Land, for the development of the first Australian base. Despite very heavy sea ice, the ship reached its objective and the first station was built. Law named it Mawson after the famous Australian scientist and explorer Sir Douglas Mawson. Leaving a ten-man wintering team, Law directed the ship on an easterly exploration cruise along the coast, and into a violent storm in sea ice from which they were very lucky to emerge safely.

During the following southern summers Law chartered polar ships from the Lauritzen Company. They sailed south from Melbourne to the stations, which were resupplied and had their wintering teams changed over before cruises were made along the coast of Antarctica. Using the ship held in the pack ice as a base, Law led teams of specialists exploring the islands and rock outcrops, landing by motorboat or sledging over the ice (helicopter transport came later). Surveyors mapped the locations' positions, magnetic measurements were made by geophysicists, and geologists and biologists made their recordings. These activities were often hazardous due to the weather and sea ice conditions. Nevertheless, during Law's directorship, the whole of Australian Antarctica was mapped.

At Mawson each year, scientific researches and data recordings of geoscience effects were developed, and glaciologists and geologists sledged southwards over the Plateau. In 1957 a second station, Davis, was built in the Vestfold Hills. When the international science associations declared 1957–1958 the International Geophysical Year (IGY), the three Australian polar stations (Mawson, Davis, and Macquarie Island) were very well prepared. The US installed a station, Wilkes, in the central part of Australian Territory, which they operated during the IGY. Law visited the US in 1958 and arranged for Australian teams to take it over; Australia still operates a Casey station at that site, although the station has been rebuilt several times.

In 1966 Law resigned from direct activity in Antarctic explorations to become executive vice-president of the Victoria Institute of Colleges. He retired in 1977. In recent years he has accompanied tourist ships to Antarctica as a lecturer.

MALCOLM KIRTON

See also **ANARE/Australian Antarctic Division; Australia: Antarctic Program; History of Antarctic Science; International Geophysical Year; Mawson, Douglas; Oases**

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LEOPARD SEAL

The leopard seal *(Hydrurga leptonyx)* population is estimated to be 222,000–440,000. These seals were not hunted by sealers, who had little interest because their blubber is not thick enough to produce much oil and their skins have never been of significant commercial value. Today they are considered to be common but are difficult to see in large numbers because of their solitary nature.

The main leopard-seal population remains within the circumpolar Antarctic pack ice, but seals are regular, although not abundant, visitors to the sub-Antarctic islands of the Southern Ocean and to the southern continents. The most northerly leopard-seal sightings are from the Cook Islands.

Leopard seals use the ice floes of the pack ice to haul out on each day to sleep. They prefer smaller ice floes, from 2 to 20 m in diameter. The amount of pack ice varies with the seasons. It is at a maximum extent between August and October and a minimum between February and March. The number of seals within an area is inversely related to the amount of pack ice that is available to them.

Adult leopard seals do not seem to migrate. Tagged seals have remained within the Antarctic pack ice within the same region over many years. Surprisingly, for seals that drift as they sleep hauled out on moving ice floes, they are relatively sedentary. Satellite-tracked seals move at speeds and distances comparable to the movement of the ice floes they haul out on. However, young seals appear to be more mobile. Subadult seals move north during the winter and small numbers are seen on the sub-Antarctic islands. Perhaps, as the younger seals do not need to remain within the pack ice to breed, they can escape food shortages during winter by dispersing northwards.

The number of leopard seals on the sub-Antarctic islands varies on a 4- to 5-year cycle. This is correlated with oscillating current patterns of the Antarctic Circumpolar Wave. Perhaps this is causing resource shortages in those years. Individuals can exceed 20 years of age.

Leopard seals are relatively large seals with reverse sexual dimorphism where the females are larger than the males. Females grow up to 3.8 m and weigh up to 500 kg, males up to 3.3 m and 300 kg. The head of the leopard seal is disproportionately large and the female's skull attains a greater length and is more massive than the male's. Both the hind- and the foreflippers are long and powerful, with the first and fifth digits of the hind flippers broadly palmate at the tips beyond the nails.

Male leopard seals are sexually mature by 4.5 years and females by 4 years of age. Females give birth to a single pup and wean it on the ice floes of the Antarctic pack ice. Length at birth is about 120 cm. Births are believed to occur from October to mid-November and mating from December to early January, after the pups have weaned. The mothers nurse their pups for up to 4 weeks. Males do not remain with the females through lactation as with crabeater seals, and only mother–pup pairs are observed on the ice floes. Mating in the wild has been observed rarely, but captive seals mate only in the water. There is a period of delayed implantation from early January to mid-February. Implanted fetuses have been found after mid-February when the corpus luteum has begun to increase in size and the corpus albicans from the previous pregnancy is regressing.

Leopard seals are highly solitary. Individual seals are widely distributed at densities ranging from 0.003 to 0.151 seals/km^2. However, there appears to be an age-related difference in their spatial behavior, because juveniles may be seen close together, even on the same ice floe.

Leopard seals are spectacular hunters and are at the top of the Antarctic food chain, taking a range of prey types—penguins, seals, fish, and krill—although this varies at different times of the year. During spring and summer, penguins and seals become important in the diet. Penguins that are captured from under the water are flicked violently as the seal surfaces to dislodge chunks of flesh. Young crabeater seals hunted soon after weaning learn to roll to avoid the leopard seals' canines. This leaves two parallel rake marks on the surviving seal and most crabeater seals (78%) bear the scars of an encounter with a leopard seal. During winter, fish and krill become important. Krill are captured by straining mouthfuls of water through their unusual three-cusped, interlocking molar teeth. Although there have been many reports of leopard seals chasing or stalking people in Antarctica, there has only been one incident where a human has been killed by a leopard seal.

Acoustic behavior is important in the mating system of the leopard seal. Leopard seals become highly vocal before and during the breeding season. Male seals sing underwater for long periods each day from early November through to January. Individual males sing distinctively different patterned songs. Female leopard seals also use long-distance acoustic displays during the breeding season. However, the females sing for only a brief period from the beginning of oestrus until they have been mated. This is presumably to advertise that they are receptive to mating. The calls of the leopard seal are low-to-medium frequencies and so powerful that they can be heard through the air–water interface and felt vibrating the ice.

TRACEY L. ROGERS

See also **Coastal Ocean Currents; Crabeater Seal; Fish: Overview; Pack Ice and Fast Ice; Penguins: Overview; Sealing, History of; Seals: Overview; Zooplankton and Krill**

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LICHENS

Lichens are a Phylum (Ascomycota) of cryptogams (spore-bearing organisms). However, they are unique as each lichen is a composite of an alga (photobiont) and a fungus (mycobiont) living symbiotically and creating a specific structural form usually unlike either of the symbionts. The alga is the photosynthetic component providing carbohydrates and energy for growth, while the fungus provides the organism's structure and is responsible for the uptake of water and nutrients from its substrate and the atmosphere. The fungal component is the major structural part of the lichen (thallus) and is responsible for the production of spores (i.e., sexual reproduction), although most species can also reproduce asexually by various types of vegetative structures. In some species the photobiont is a cyanobacterium (blue-green alga). Since the dominant component of lichens is a fungus (which is a microorganism deriving its energy saprophytically from decaying organic matter), lichens should strictly be referred to as lichenized fungi and not as plants (which contain chlorophyll and obtain their energy through photosynthesis). Lichens have a remarkable capacity to survive in extremely severe environments; they are capable of withstanding long periods of drought as well as enduring fluctuations in thallus temperature (e.g., from –20°C to 40°C within a few hours in polar and alpine habitats).

The lichen thallus develops a characteristic structure with a distinct growth form, largely dependent on which species of fungus and alga combine. How this selection is made is largely unknown, but a germinating lichen (fungus) spore develops thread-like strands (hyphae), which grow over the substrate "foraging" for a specific algal partner. Once this happens, the hyphae envelop the alga, both multiplying and developing a structure, predominantly fungal in nature but with layers of photosynthetically active algal cells just below the surface. However, most lichens are capable of dissemination and colonization by means of specialized vegetative structures that contain both fungal and algal components, and are therefore instantly ready for developing a new thallus when substrate conditions are favourable. Lichens have a wide range of structural shapes (growth forms), usually only a few centimetres in diameter or height, but some achieve much greater dimensions. They are typically slow-growing and long-lived, and exceptionally large thalli are of great antiquity; estimated ages of from 500 to over 5000 years have been reported for individual thalli.

Antarctic lichens are well adapted for survival in low temperatures and can achieve substantial rates of photosynthesis (production of carbohydrates required for growth from carbon dioxide in the presence of sunlight and water) well below 0°C. Very low rates of carbon assimilation have been recorded at temperatures of –10°C to –17°C in a few continental species (e.g., *Umbilicaria aprina*). Even at subzero air temperatures, the microclimate in which the lichen is growing can be 20°C to 30°C above ambient. The optimum temperature for net photosynthesis in most maritime Antarctic species is <5°C, and for continental species <3°C. However, photosynthesis ceases when the thallus is exposed to very strong sunlight (photoinhibition) when it becomes very warm and quickly desiccates. Thus photosynthesis is very intermittent, and this greatly restricts growth.

Diversity and Biogeography

Because of their unique physiological tolerances, lichens are the predominant terrestrial life form throughout much of Antarctica, particularly the drier and more windswept habitats. In suitable areas, especially at coastal sites, they may cover several hectares of rocky terrain. About 420 species are known, with the greatest diversity (about 75%) occurring in the maritime Antarctic (western Antarctic Peninsula, South Shetland Islands, South Orkney Islands, and South Sandwich Islands). About 90–100 species are known from continental Antarctica (excluding the western Antarctic Peninsula). Unfortunately, no Antarctic lichens have common names. The majority have a close affinity with southern South American flora, from where they have originated. However, many also occur in New Zealand, which reflects the Gondwanan origins of much of the flora before the tectonic breakup of that ancient landmass. About 25% of the lichens have a bipolar distribution, occurring, and probably evolving, in the Arctic and northern temperate regions and reaching the opposite end of the planet by "mountain-hopping" along ranges connecting the Northern and Southern Hemispheres, such as the Rockies–Andes chain. About 10% of the Antarctic lichen flora have a worldwide distribution. The early isolation of the continent from other landmasses has led to a large number of lichens' evolving as endemics (about one-third of the maritime Antarctic species and c. 50% of continental Antarctic species).

Growth Forms

The majority of species have a crustose (encrusting) or microfoliose (minutely leaf-like) growth form in which the thallus closely adheres to the substratum, which is usually rock, although some colonize soil and moss. These are sometimes referred to as microlichens. Each thallus can reach several centimetres across, and where many of these coalesce multicoloured patches of several species can cover several square metres of rock. Many of these lichens are brightly coloured, due mainly to anthraquinone pigments, and are nitrophilous (i.e., having a requirement for nitrogen). They often grow extensively on coastal rocks close to penguin and other seabird colonies. The typical orange-colored lichens include numerous species of *Caloplaca, Candelaria, Candelariella,* and *Xanthoria,* while other colourful nitrophilous genera including *Acarospora, Amandinea, Buellia, Haematomma, Lecidea, Lecanora, Verrucaria,* and several others add a splash of white, grey, yellow, brown, and black to the rock. Away from the influence of birds, rock surfaces are often covered with a mosaic of nitrophobous (nitrogen-avoiding) crustose lichens, such as *Acarospora* (yellow), *Lecanora* and *Lecidea* (various colours), *Placopsis* (pink), *Pleopsidium* (yellow), *Rhizocarpon* (green), *Tephromela* (white), etc., while soil may be colonized by large patches of powdery white or greenish encrustations of *Lepraria* and *Leproloma*.

The larger, more prominent but less diverse macrolichens include the foliose (leaf-like), squamulose (thallus comprising a mass of scale-like lobes), and umbilicate (attached centrally by a stalk to rock) growth forms, mainly growing on rock, and the bushy, much-branched fruticose growth form, again mainly on rock, but some of these also colonize mosses. Foliose species are mostly lithophytes (growing on rock), attaching to their substrate by root-like rhizines, but a few grow on mosses or coarse soil. Most foliose species occur in coastal habitats and seldom reach altitudes above a few hundred meters. Several are nitrophilous, occurring near bird colonies, notably species of *Dermtocarpon* (grey), *Flavoparmelia* (yellow), *Parmelia* (brown), *Physcia* and *Physconia* (grey), *Turgidosculum* (black), and *Xanthoria* (orange). Moss- and soil-inhabiting genera include *Leptogium* (black), *Peltigera* (grey-brown), and *Psoroma* (greenish-brown, squamulose growth-form). *Turgidosculum complicatulum* is the lichenized form of the green foliose nitrophilous alga *Prasiola crispa,* which is very abundant in wet areas around bird colonies. *Leptogium puberulum* is one of the very few lichens that prefer wet habitats such as seepage areas on rock faces and below melting snow patches. This is because its photobiont is the cyanobacterium *Nostoc,* which, in its free-living state, grows in similar wet sites. Only a few species of umbilicate lichens occur in Antarctica, all belonging to the genus *Umbilicaria*. Of these, *U. antarctica* are particularly abundant on sheltered coastal cliffs in the maritime Antarctic and can reach exceptional size, although their plate-like thalli are reduced to a ragged leathery structure by wind and ice action. The largest recorded thallus, on a rock face on Signy Island, South Orkney Islands, measured c. 45 x 25 cm. *U. decussata* has much smaller thalli, attaining only 1–2 cm diameter in exposed habitats. However, this remarkably cold- and drought-tolerant lichen is one of a small group that grow as a community throughout continental Antarctica in one of the most severe environments on Earth. They also occupy similar habitats in the high Arctic.

The fruticose lichens are amongst the most prominent Antarctic lichens, again found mainly in the maritime Antarctic. The often large bushy genus *Usnea* is very abundant, notably *U. antarctica* (grey-green) and *U. aurantiaco-atra* (grey-yellow), festooning cliffs and covering rocky hillsides. The latter usually have many large black disc-shaped apothecia, the spore-producing structures of lichens. Coastal cliffs near seabird colonies may also have large strap-shaped yellow thalli of *Ramalina terebrata,* while exposed ridges and plateaux in the northern maritime Antarctic are often colonized by a similar black species, the endemic *Himantormia lugubris*. Sometimes associated with the *Usnea*s and *Umbilicaria antarctica* on sheltered cliffs are long straggling thalli of the black lichen *Bryoria austromontana,* which can attain exceptional lengths of over 40 cm. Several fruticose lichens grow directly on mosses and soil. In some communities, various mosses and often brightly pigmented lichens create a surprising patchwork of colour. These may include *Alectoria nigricans* (grey-buff), *Bryoria implexa* (black), *Cetraria aculeata* (purple-brown), *Coelopogon epiphorella* (brown), *Sphaerophorus globosus* (orange-brown), *Stereocalon* spp. (white and pinkish-grey), and the ubiquitous *Usnea antarctica*. The black *Usnea sphacelata* and *Pseudephebe minuscula* are two of the most stress-tolerant lichens, occurring almost exclusively in the harshest environments of continental Antarctica. Together with their usual associates, *Buella frigida* and *Umbilicaria decussata,* these species contain dark pigments that protect the thallus from potentially damaging ultraviolet radiation, which is much greater at high latitudes and altitudes. Another genus of fruticose lichens, *Cladonia,* has many species in the maritime Antarctic, all growing on moss or soil. They commence as a primary thallus of scale-like structures (squamules), which usually disappears once the secondary thallus develops. This is an erect hollow tubular structure (podetium), occasionally branched, and often terminating in a cup-like scyphus.

Ecology of Lichen-Dominated Communities

Throughout the Antarctic biome, lichens are the dominant plants in all but the wettest habitats, with a very few exceptions. However, their occurrence and the development of communities are restricted by local environmental conditions, notably instability of the substratum (e.g., cryoturbation of soil and stones, exfoliation of rock surfaces), rock type and surface texture, permanent shading from direct solar radiation, excessive exposure to strong wind, the abrasive action of wind-blown mineral particles and ice crystals, and, in the close proximity of birds and colonies, the impact of disturbance and toxic levels of certain chemical elements. Some species exist in profusion and form distinct communities in habitats receiving nutrient enrichment (especially from nitrogenous compounds in meltwater runoff and in aerosol form) from seabird colonies, although even in some nutrient-deficient habitats lichens may develop dense stands.

In the northern maritime Antarctic, diverse communities of nitrophilous lichens (e.g., *Acarospora, Buellia, Caloplaca, Haematomma, Huea, Physcia, Ramalina, Xanthoria*) cover large expanses of sea cliffs and coastal boulderfields influenced by a nutrient aerosol derived from nearby seabird colonies. On a much smaller scale, species of *Candelaria, Candelariella, Physcia,* and *Xanthoria* form a colorful community on moribund moss cushions in continental Antarctic sites. Breeding colonies of snow petrels *(Pagodroma nivea),* on inland nunataks, sometimes several hundred kilometres from the sea (notably in Dronning Maud Land) and at quite high altitude, are relatively lichen-rich oases. Here, nitrophilous lichens (especially *Caloplaca* and *Xanthoria* spp.) form a distinctive community in an otherwise barren landscape. These bird-influenced communities of brightly colored lichens can be seen from a long distance away. Indeed, J. D. Hooker, the naturalist on Sir James Clark Ross' 1839–1843 expedition, remarked of an orange species of lichen: "This plant forms the most curious feature in the botany of Cockburn Island [off the northeast Antarctic Peninsula], a desolate spot of land on the extreme limit of southern vegetation; for there it abounds so as to stain the rocks, and render the colour thus produced visible for many miles. It is partial to the effluvium from decaying animal matter [Adélie penguins and blue-eyed cormorants]..."

Although few lichens occupy wet habitats, several salt-tolerant species frequent rocks inundated by sea spray and occasional temporarily inundated by high tides. However, *Verrucaria serpuloides* is the only true marine lichen known, occurring as very thin black thalli on permanently submerged rocks at depths of 1–10 m in the mid-Antarctic Peninsula region.

The most extensive stands of lichen vegetation, sometimes covering several hectares, occur in the maritime Antarctic region, where favourable habitats, notably raised beach terraces and rocky hillsides near the shore, support spectacular communities dominated particularly by *Usnea antarctica, U. aurantiaco-atra, Himantormia lugubris,* and *Umbilicaria antarctica* in the South Orkney and South Shetland Islands. *Pseudephebe minuscula, Umbilicaria decussata,* and *Usnea sphacelata* occupy similar habitats in the southwestern Antarctic Peninsula region, and also throughout coastal continental Antarctica, locally extending to inland sites often at high altitude. In fact, the latter community (invariably with *Buellia frigida,* and usually *Lecidea cancriformis* and several other crustose species) is remarkable for its consistency of species composition and tolerance of exceptionally cold, dry, and windy conditions. The black thalli of *U. sphacelata,* in particular, often develop stands covering from a few square metres to several hectares on windswept ridges that probably receive almost no winter snow cover, thereby exposing the plants to temperatures below –50°C and relative humidity often below 20%. Its remarkable survival capacity may be because such stands usually occur in areas where clouds commonly form, thus providing a source of atmospheric moisture that lichens are capable of absorbing.

Another prominent coastal lichen community in the maritime Antarctic is dominated by *Umbilicaria* *antarctica* and *Usnea antarctica,* which festoon coastal rock faces, often with exceptionally large thalli in sheltered habitats. Coastal rocks often exhibit a distinct vertical zonation of communities along a hygrohaline (salt water) gradient from below the high water mark to several metres above it, dominated by species of *Acarospora, Buellia, Caloplaca, Lecidea, Verrucaria,* and several other genera. Nonbiotically influenced habitats from near sea level to about 2500 m altitude are often dominated, either abundantly or, in the latter instance, very sparsely, by nitrophobous saxicolous species of yellow *Acarospora, Carbonea, Lecidea, Lecanora, Rhizocarpon, Rhizoplaca, Buellia frigida, Pleopsidium chlorophanum, Pseudephebe minuscula, Umbilicaria decussata,* and *Usnea sphacelata*.

A distinct lichen community occurs on stands of bryophytes. The thick moss turf banks formed by *Chorisodontium aciphyllum* and *Polytrichum strictum* throughout the northern maritime Antarctic support an association of loosely attached fruticose lichens and several crustose species. These include the fruticose *Alectoria nigricans, Bryoria implexa, Cetraria aculeata, Cladina rangiferina* and several *Cladonia* spp., *Coelocaulon epiphorellum, Sphaerophorus globosus, Stereocaulon* spp., *Usnea antarctica, U. aurantiaco-atra,* and crustose *Ochrolechia frigida, Rinodina olivaceobrunnea, Lepraria/Leproloma* spp., and occasional other species. Extensive stands of the mosses *Andreaea* spp., and locally *Bucklandiella suedica* and some other bryophytes, usually have many of these lichens associated with them, usually with a few foliose species (e.g., *Massalongia carnosa, Pannaria austro-orcadensis, Psoroma cinnamomeum,* and *P. hypnorum*).

Throughout the northern maritime Antarctic the current trend of regional climate warming has caused substantial recession of ice field and glacier margins and considerable thinning since the mid-twentieth century. This has revealed many subfossil (a few hundred to several thousand years old) moss turf banks that have retained their original structure and species composition intact. Within the permafrost of such banks many of the present-day macrolichen associates can be clearly identified, as can others on recently exposed rock ledges. However, there is no evidence that any species existed earlier in the Holocene that do not occur at present.

Some introduced substrates in the northern maritime Antarctic are colonized by lichens. Several crustose and foliose species as well as *Usnea antarctica* may be found on weathered and decaying timber associated with human habitation. Timber originating from the 1920s whaling station on Deception Island, South Shetland Islands is heavily colonized by many lichens, as is wood dating from whaling activities at Signy Island about the same period. Concrete foundations and walls of old buildings at many Antarctic stations have been colonized by mainly crustose lichens, especially *Caloplaca* spp., and other anthropogenic materials (e.g., leather, iron, glass) also serve as a substrate for lichens. Whalebone on raised beaches throughout the maritime Antarctic often has a variety of lichen colonists.

Lichens in Extreme Habitats

Most habitats in interior continental Antarctica can be regarded as extreme, in terms of low temperature, prolonged drought, rapidly fluctuating thermal and hydric regimes, high solar irradiance and ultraviolet-B radiation levels, and prolonged winter darkness. Despite these physiologically stressful conditions, lichens have been found in almost all areas where there is ice-free rock, including those closest to the South Pole (at least 15 species beyond 85° S, with three species, *Carbonea vorticosa, Lecidea cancriformis,* and *Sarcogyne privigna,* at 86°29′ S in the La Gorce Mountains). About 25 species have been recorded above 2000 m altitude, with a few collected at around 2500 m (e.g., *Acarospora gwynnii, Buellia frigida, Pseudephebe minuscula, Rhizocarpon geographicum, Rhizoplaca melanophthalma, Umbilicaria decussata*). This appears to be the altitudinal limit at which lichens can survive in Antarctica. At these elevations and at far more southerly latitudes, epilithic (growing on rock) lichens must be exposed for long periods to temperatures as low as –60°C to –70°C in winter (no sunlight to warm the substratum, and usually no insulating snow cover on windblown rock faces) and a summer diurnal range of from 15°C to 20°C (thallus and substratum microclimate) to –40°C. As a probable protective response to extreme conditions, especially high UV-B levels, several lichen species have much darker or even black thalli, rather than the more typical coloration at low coastal sites (e.g., *Lecanora physciella, Rhizoplaca melanophthalma, Umbilicaria decussata, Usnea sphacelata*).

Numerous crustose lichens in extreme continental Antarctic habitats are barely visible, occurring in microfissures in rock or around the edge of large crystals. Often they exist only as apothecia (spore-producing structures), although there may be a substantial weft of fungal hyphae (rhizomorphs) within the fissure penetrating 1–2 cm into the rock (e.g., *Acarospora gwynnii, Caloplaca saxicola, Lecidea cancriformis, Rhizoplaca melanophthalma*). These morphotypes (which in less extreme habitats usually have a distinct thallus) are components of a chasmoendolithic (within rock fissures) community that is both widespread and common, although very obscure, in continental Antarctica. This reaches an extreme development in the cryptoendolithic communities that occur within the coarse crystalline structure of the Beacon Sandstone in the Transantarctic Mountains (at about 74°–78° S) in what is probably the most severe environment for life on the planet. Here, depending on the availability of moisture, various communities occur from just below the iron-stained rock surface to about 10 mm within the rock. These include, in the upper zone, a "protolichen," below which are other distinct biotic zones. In areas where there is no free water, but only atmospheric water vapour, the upper black zone, a few millimetres below the rock surface, is formed by dark brownish, greyish, or greenish masses of dark-pigmented (with melanin) fungal hyphae. These may be covered with precipitated iron compounds and often enclose groups of algal cells to form small globular bodies resembling the early stages of a lichen thallus. Beneath this is a white zone of colorless fungal filaments forming a hyphal mesh around the rock crystals, below which is a green zone formed by abundant algal or cyanobacterial cells. Below the algal zone there are sometimes transparent fungal hyphae. These communities of organisms are of particular relevance in the search for evidence of former life on the planet Mars.

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See also **Algae; Antarctic: Definitions and Boundaries; Antarctic Peninsula; British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); Colonization; Cryptoendolithic Communities; Deception Island; Fungi; Hooker, Joseph Dalton; Liverworts; Mosses; Oases, Biology of; South Orkney Islands; South Sandwich Islands; South Shetland Islands; Transantarctic Mountains, Geology of; Vegetation**

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LIGHT-MANTLED SOOTY ALBATROSS

The light-mantled sooty albatross *(Phoebetria palpebrata)* is a small and slender albatross species with a grey body, sooty brown head and wings, and conspicuous white eye crescents. Light-mantled sooty albatrosses weigh about 2.5 to 3.5 kg and have a wingspan of 1.8 to 2.2 m. The bill is slender with a blue-purple stripe on the lower mandible. The juveniles and immatures appear broadly similar to the adults.

Light-mantled sooty albatrosses are evaluated by Birdlife International as "near threatened," as it is considered that the species is close to qualifying, or is likely to qualify, for the "threatened" category in the near future. The total annual breeding population is estimated to be 19,000 to 24,000 breeding pairs, equivalent to 58,000 mature individuals in this biennially breeding species. Light-mantled sooty albatrosses breed at South Georgia (jurisdiction of United Kingdom); Prince Edward and Marion Islands (South Africa), Île Amsterdam, Île St. Paul, Îles Crozet, and Îles Kerguelen (France); Heard Island and Macquarie Island (Australia); and the Auckland, Campbell, and Antipodes islands (New Zealand). The largest populations are at South Georgia, Îles Kerguelen, and the Auckland Islands, but the population trends for this species are largely unknown.

One Îles Crozet population has decreased by 13% since the 1980s and the population on Marion Island is reported to have decreased since the late 1990s. The population on Macquarie Island, which constitutes about 5% of the global population, appears to have remained relatively stable since the 1990s.

Light-mantled albatrosses commonly nest on vegetated ledges or cliffs, which may be situated in either coastal or inland locations. The nests are usually a low cone, constructed of mud and vegetation, and are either solitary or in small groups. Adults return to the colonies during September or October, depending on breeding site. Egg laying is well synchronised and occurs from late October to early November. Both adults alternate in incubating the single egg for 10 weeks until the egg hatches in late December to early January. Chicks fledge in late May to early June at 5 months of age. Light-mantled sooty albatrosses are generally considered biennial breeders, although many adults may defer breeding for more than one season after a successful breeding attempt. Birds return to their natal islands from 6 years of age, and begin to breed at between 7 and 12 years old. The critical demographic parameters of adult and juvenile survival are largely unknown for this species.

Light-mantled sooty albatrosses are dispersive and solitary at sea and have a widespread and circumpolar distribution, ranging from the Antarctic pack ice northwards to 35° S. Limited satellite tracking has shown extensive movements achieved through rapid flight to foraging areas that are visited repeatedly. Birds from Macquarie Island travelled over 1500 km to their foraging grounds south of the Antarctic Polar Front. During the nonbreeding season their range extends northwards and includes subtropical waters in the Australian, New Zealand, and South Pacific Ocean.

The diet of light-mantled sooty albatrosses varies with location; fish, squid, and crustaceans are all important prey items. Feeding behaviours include surface seizing and plunging, and dives to depths of 12 m have been recorded for this species.

Light-mantled sooty albatrosses are known to be killed in longline fisheries, although the level of bycatch for this species on the high seas is uncertain. Their capture during longline operations targeting tuna has been confirmed in Australian and New Zealand waters, and there is also concern over longline interactions in operations targeting Patagonian toothfish *Dissostichus eleginoides*. Introduced predators on some of their breeding islands are also thought to impact this species.

ROSEMARY GALES

See also **Albatrosses: Overview; Amsterdam Island (Île Amsterdam); Auckland Islands; Campbell Islands; Crozet Islands (Îles Crozet); Heard Island and McDonald Islands; Kerguelen Islands (Îles Kerguelen); Macquarie Island; Polar Front; Prince Edward Islands; St. Paul Island (Île St. Paul); South Georgia; Toothfish**

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LIVERWORTS

Liverworts belong to the Plant kingdom division Marchantiophyta (formerly, with the mosses, Bryophyta), which comprises two classes (Marchantiopsida and Jungermanniopsida). Mosses and liverworts are still referred to collectively as bryophytes. Genera and species of both, in several orders and families, are represented in the Antarctic.

Growth Forms

Liverworts have two principal morphological forms. The predominant growth form comprises many individual leafy, often unbranched, shoots (Jungermanniopsida), the whole structure being referred to as a colony of shoots. Many of these grow as erect colonies, but others form an interwoven mat of prostrate shoots, sometimes of very small dimensions. The thalloid growth form (Marchantiopsida) is rare in the Antarctic. These are flat strap-shaped plants adhering closely to their soil or rock substrate.

Physiology

The physiology, growth, and reproduction of liverworts are very similar to those of mosses. Their simple anatomical structure, without specialized water-conducting tissues, restricts liverworts to moist habitats, from which they derive their water and nutrients passively and uncontrollably through their leaves and stems. Like mosses, they have no control over water loss during dry or sunny weather, which is a major factor restricting their occurrence to moist habitats. Very few Antarctic species reproduce sexually (i.e., produce sporophytes and viable spores), and even then they do so only very rarely. Most rely on dispersal and establishment by vegetative means, for example, detached shoot fragments or specialized structures such as tiny tubers and gemmae (small multicelled propagules capable of developing into new plants in favourable habitats).

Species Diversity and Biogeography

Most liverworts are generally very inconspicuous components of Antarctic vegetation, almost invariably associated with mosses and often hidden among the moss shoots. All grow in coastal areas, with very few occurring more than 2 km inland. A recent revision of the liverwort flora of the Antarctic, including the South Sandwich Islands and Bouvetøya (climatically and biologically an extension of the maritime Antarctic) listed a total of twenty-seven species in nineteen genera. This is less than a quarter of the moss flora for the biome; a similar number could be found on a single tree trunk in a tropical rain forest. Only one species *(Cephaloziella varians)* occurs in continental Antarctica. Several are restricted to geothermal habitats on the South Sandwich Islands. As with mosses and lichens, no Antarctic liverwort species have common names. Nine species have a sub-Antarctic distribution, eleven are southern temperate, six are bipolar, and one *(Marchantia polymorpha)* has a global distribution, although it was recorded only once as a new colonist on recently created heated ground following an eruption on Deception Island, South Shetland Islands, and has not been seen since. The greatest diversity of species is in the milder, wetter South Orkney and South Shetland islands, although several extend southwards along the west side of the Antarctic Peninsula, with only two species reaching 68° S (*C. varians* and *Barbilophozia hatcheri*). Seventy-five percent of the Antarctic liverwort flora occur on the tiny Signy Island, in the South Orkneys. Many species are rare or are known at very few sites in the Antarctic, and several are restricted to the unique geothermal habitat associated with volcanic activity.

Ecology

Liverworts rarely develop distinctive communities in the Antarctic, although several species occur frequently, if sparsely and inconspicuously, in moss-dominated communities in moist habitats. Loosely aggregated shoots of liverworts often occur intertwined amongst moss colonies, especially species of *Andreaea, Bucklandiella,* and *Schistidium* in fellfield communities, *Sanionia* and *Warnstorfia* in seepage areas and bogs, and the thick turf-forming *Chorisodontium aciphyllum* and *Polytrichum strictum*.

Occasionally liverworts dominate over mosses in some communities, and very occasionally a few species form pure stands of more than 1 m^2. *Cephaloziella varians* is by far the most common and widespread species, occurring almost invisibly in many plant communities throughout the maritime Antarctic. It is also the only liverwort that extends to continental Antarctica, where it reaches 77°00′ S at Cape Geology, Botany Bay, southern Victoria Land. Several species occurring on heated ground around fumaroles on several of the volcanic South Sandwich Islands archipelago in the northern maritime Antarctic form mixed communities dominated by liverworts unknown elsewhere in the Antarctic (e.g., *Clasmatocolea rigens, Riccardia georgiensis, Triantrophyllum subtrifidum*); *Cryptochila grandiflora* also occurs here, and around a single fumarole on Deception Island, South Shetland Islands. The large thalloid species *Marchantia berteroana* is locally common on some northern maritime Antarctic islands (notably Signy Island, South Orkney Islands), forming conspicuous mats of overlapping strap-shaped stems.

Because of their physiological intolerance of dry and cold conditions, liverworts are restricted to low-altitude habitats, mainly in coastal areas. A few (e.g., *Cephaloziella varians, Barbilophozia hatcheri*) are found at up to 350 m altitude. However, there is a unique occurrence of *C. varians* on geothermal ground on Cryptogam Ridge, near the summit of the volcano Mt. Melbourne, Victoria Land, at c. 2700 m. Here, soil surface and vegetation temperatures reach over 30°C, maintaining a warm humid environment throughout the year for this liverwort and the moss *Campylopus pyriformis*. While several mosses exist in a permanently submerged environment in Antarctic lakes, so far there are no known exclusively aquatic liverworts.

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See also **Antarctic Peninsula; Bouvetøya; Deception Island; Mosses; South Orkney Islands; South Sandwich Islands; South Shetland Islands; Streams and Lakes; Vegetation**

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LIVING IN A COLD CLIMATE

With no indigenous human population in the Antarctic and the first documented explorers reaching there in the last 4 centuries, the development of a transient population is a most interesting one. The success of humans in Antarctica has depended more on behavior and technology than on biology. The Antarctic population, which spends from a few days to no more than 2 years at a time in Antarctica, survives because of the clothing, food, and shelter available. All survival needs, with the exception of water, must be taken with them. As all water is frozen as ice, considerable energy to melt the ice must also be available. Despite the dramatic changes in technology since the Heroic Era, personnel are still physically isolated, especially during winter, and are subject to the same hostile and unforgiving environment. Some groups during winter are arguably the most isolated on Earth, and cannot be evacuated in the event of a health problem, injury, or mishap, unlike similar remote groups in other extreme environments, including nuclear submarines, theaters of war, mountains, caves, or the International Space Station in orbit.

Humans in Polar Regions

Humans are *tropical* animals in that evidence suggests they evolved in Africa in a hot, moist environment. Their ability to cope with cold is limited. Naked humans at rest and in still air can maintain constant body temperature at an air temperature of 27°C–29°C without raising heat production above the resting value. Mild cooling is tolerated by a rise in metabolic rate. Greater cooling initiates further heat production by increased muscle activity such as shivering, and the body conserves heat by constricting the blood vessels of the skin and shunting blood away from the surface to the body core; the skin is protected by alternating periods of vasodilatation with the vasoconstriction. Additional behavioral action such as folding the arms over the body and bending the legs, or huddling, reduces the surface area of the body and hence heat loss due to radiation and convection. Further heat production may occur by nonshivering thermogenesis, which involves complex metabolic processes.

Coastal Antarctica may not have temperatures as low as the Arctic, but high winds and frequent blizzards increase the wind chill factor and thus cooling. Although there is scientific evidence of both general and local acclimatization to cold by some of the transient Antarctic population, human survival in the colder, higher latitudes such as the Arctic, where the Inuit have lived for millennia, is not due to physiological changes, but to technical knowledge and its application.

Humans have had to overcome the isolation of Antarctica, travel great distances over rough oceans to get there, and be totally self sustaining by complex operations. In addition to cold, depending on the latitude, diurnal sunlight and darkness vary from the maximum of 6 months of summer sun and winter darkness at the South Pole.

Antarctic Populations

Today the total wintering population in the Antarctic is around 1000, almost all at national stations and bases. This number increases more than tenfold during summer, as research programs and tourist visits are at their busiest. The scientists and support personnel at the various bases are a microcosm of the society of their country. They are selected for their ability to perform specific tasks and live in a closed community. Most staff undergo training to facilitate safe living and working in Antarctica. Each country of origin organizes training according to the culture, practices, accepted norms, logistics capabilities (depending on whether travel to Antarctica is by ship or air transport), and legislative requirements (such as occupational health and safety) of the parent country. Preparation may include the development of a remote community, how they will live and interact, and how they might resolve conflict. Personnel traveling into field areas are trained in field survival techniques.

There is much variability in life in Antarctica, especially as numbers of people at bases can vary from more than 200 to less than 10 in winter, and the level of support provided can range from McMurdo Station, with a population of more than 1000 in summer, to several persons in a tent in a remote field location. Further, some groups are military, others civilian, still others a mixture of military and civilian. Most groups consist of males and females, few all-male groups remaining, and some nations have families and children in their communities. People go to Antarctica for a variety of reasons in addition to the specific objectives of research programmes, including the challenge of the environment on the job, the lifestyle, to save money, the fact that it is the last of the world's wilderness areas still relatively pristine, or to simply escape from the "real" world.

Antarctic Stations/Bases

Station facilities in Antarctica are generally modern, insulated, and comfortable. Living quarters have mess and general living areas, kitchens ranging from basic to commercial, bedrooms ranging from individual to bunk rooms, bathrooms, and recreation areas that may include a library and film theatre. Power generation, communications, research laboratories, offices, stores, and workshops may be in the same complex or in separate buildings; some are two or three stories. Other additions at the larger stations include gymnasiums, bowling alleys, or other sporting facilities for volleyball, basketball, squash, racquetball, badminton, or half tennis. Some have chapels or small churches. Few buildings are reminiscent of the Heroic Era, when members of expeditions lived in small, crowded, uninsulated huts and were often cold and suffered privation. The old huts still standing show evidence of attempts to stop the entry of interminable fine drift snow with a variety of materials such as tar paper and horsehair. Buildings have evolved from the wooden huts to wood and aluminum insulated panels. Many of these are of considerable size and complexity. Modern building design allows for both communal areas and places where people can get away if they wish. Stations that previously were buried under snow and had to be abandoned are now replaced by buildings that can be raised above the accumulating snow. Initially, buildings were prefabricated and needed to be constructed in between blizzards in a relatively short time by all staff. They are now constructed by professional teams using heavy equipment over months or years.

How Antarctic Life Has Changed

Technological advances and the experience of living in Antarctica have dramatically altered life there. Long sea voyages by wooden sailing ships, some with steam power, through the stormiest seas on Earth and penetration of the short austral summer sea ice are now replaced by the much faster ice breakers and air transport. Intense physical labor to unload ships at the ice edge and transport buildings, stores, and equipment across the sea ice by dogs, ponies, and man-hauling is now accomplished at wharves by cranes and industrial plants, often with assistance from helicopters. Coal and coke were once the primary source of heating and cooking energy; they were later replaced by electricity and gas appliances, with heating also coming from the cooling systems of the power house. Fossil fuel use is being substituted for by wind and solar power. Paraffin lamps and candles were initially replaced by acetylene generators before being replaced by electricity.

Early groups communicated by leaving messages on snow and rock cairns for summer ships and field parties. Wireless was introduced by Douglas Mawson's Australasia Antarctic Expedition in 1911–1914. Polar cap absorption (PCA) caused lengthy radio blackouts of days to weeks on end. Communications progressed from use of Morse key to radiotelephone, teleprinters, and finally "blackout-free" satellite communications. Satellite phones are used in the field along with other light-weight, reliable hand-held radios, thus eliminating the need for hand cranking generators to power unreliable and heavy radios. Communications is one area that has altered Antarctic isolation, although people may still be totally physically isolated. Use of satellites for phone, fax, scientific data transmission, email, and internet access is common. Navigation is another totally altered system. The Global Positioning System (GPS) and radar now provide accurate and safe navigation to those traveling in Antarctica.

The great physical effort to collect snow and ice and melt them for water has been changed by modern technology of desalination plants in coastal areas and heat probes into the ice, or heavy equipment to gather snow. Old rituals such as the bath in front of the stove while the individual was on night watch every week or two are long since gone. Snow baths in the field may still be the norm when camping in remote areas, but showers are found on tractor trains and at inland camps. Water is still at a premium in Antarctica, and some stations with large populations must restrict each person to several short-duration showers per week. Pit toilets have transitioned through putting waste untreated into the sea, to gasoline and natural gas fired systems and flush toilets and sewage systems, with the sludge from the treatment facilities being removed from Antarctica. Similarly, field toilets have progressed to all waste being retrograded to the coastal stations.

Routine man-hauling, dog sledging, and use of ponies have been replaced by mechanical transport, helicopters, and fixed-wing aircraft. Improvements in clothing and field equipment have altered life in Antarctica. Technological changes in scientific equipment have also resulted in a marked change in the range of research work that can be carried out in Antarctica. Computers, satellites, and sophisticated scientific laboratories are in sharp contrast to some of the primitive scientific equipment used only decades ago. Technology has been important from the first days of humans in Antarctica, but with the rapid changes of the last 50 years, living and working in Antarctica has been and will continue to be improved.

Station/Base Life

Living in Antarctica is little different to living in any other remote, extreme environment, despite Antarctica's being the coldest, highest, driest, windiest, and most isolated continent on Earth. However, those going to Antarctica travel great distances over the most inhospitable oceans and, if air transport is not available, are not able to get out for long periods of the year. High winds and blizzard conditions occur regularly, making movement outside difficult without the use of ''blizzard lines'' or supporting ropes between buildings to prevent people from becoming lost.

Antarctic stations or bases are like small remote towns, as all services must be provided. All have a designated leader or commander, but most work as classless societies with everyone supporting the scientific and other (e.g., art, education) programs. People are very dependent on each other. Most staff have multiple skills, as not all disciplines or occupations normally found in society are represented in the remote communities. Libraries are found universally, but there are no trained librarians, and for the most part the sole doctor, who provides all health-care needs, is aided by ''amateur'' assistants. Scientists may not have the full range of technical support, as they do at a university or research establishment, and therefore must depend on the skills of those present. There are generally no prospects of getting the services of an expert on call. An amazing breadth of skills, and the ability of the staff to improvise, are found on an Antarctic base.

Life is less complex than in society at large. People do not have to conform to many conventions, such as dress, or travel distances to work. This may cause problems as, freed of the routine of normal society, some individuals have difficulty adapting to the less conventional working and social arrangements. Most staff, however, have competed to work in Antarctica, and are self-motivated and committed to accomplishing the tasks they have been selected to perform. There is a basic work output necessary for the safety and well being of each group. Some individuals on a base may have little in common culturally and may not be socially compatible. It is life in a test tube, as all live in close contact. Groups from the same country of origin, living at different geographical locations in Antarctica at the same time, may react to common problems or edicts in very different ways. It depends on the group, the individuals, and leadership, and defies prediction from group to group and year to year. Groups develop customs, rituals, and language to such a degree that dictionaries of specific Antarctic words, terminologies, and usage have been written.

Recreation is an important aspect of base life, and centers around social, musical, sporting, and intellectual activities; the country of origin influences those significantly. National holidays and events are celebrated, many having additional ''Antarctic'' customs and rituals added to the event. Small groups celebrate individual birthdays and anniversaries with highly organized parties and dinners, international cuisine being prepared on most stations. The isolated communities form bands, theatrical, sporting, musical, and dining groups and societies, depending on the size of the base. Mid-winter—celebrated around the shortest day in June—is a strong Antarctic tradition, being observed since the Heroic Era. It may last several days with banquets, plays, rituals, and sporting events. The international aspect of Antarctic life is reflected in events staged between bases in the same locality or competitive events such as chess or darts competitions, conducted at a distance across the continent by radio. Most take advantage of the unique Antarctic landscape to enjoy the outdoors in snow and ice pursuits, observing the seasonal wildlife, photographing the rugged landscape, or just getting away for a few days on a field trip.

Field Life

Despite the disadvantages of layers of polar clothing and the lack of the comforts of a heated base with regular meals and recreation, field life is most rewarding and eagerly looked forward to. Those on either logistic or scientific tractor trains have vans to live in that are more comfortable than tents when the train is stationary, but most uncomfortable as they ride roughly over the wave-like sastrugi at very low speeds of around 5 km/hour for most of the day. Motorized toboggans, four-wheeled motorcycles, and larger all-terrain tracked vehicles have enabled faster speeds and greater mobility when compared to manhauling, skiing, or dog travel, even though the latter, to those who have used it, remains the ultimate in polar field life. In the field, fixed camps may have prefabricated huts of various sizes and description, or large, heated tents. Mobile parties carry a tent—ranging from the classical tetrahedral, polar pyramid with its four poles, square base, sewn-in floor, and double walls to the more modern compact mountaineering and expedition tents. The tents provide safe shelter in the most trying of blizzard conditions.

A polar pyramid tent can be pitched in minutes by one person in calm weather, but in high winds it is a more difficult task that needs rehearsing to allow the wind to assist in the erection. The tubular entrance to the tent is faced across the wind to decrease snow accumulation. The flap surrounding the tent is secured by placing blocks of snow on it, cut by snow shovel or saw; some tents have additional tie-down ropes and pegs to anchor the flap to the snow. Two people usually occupy the tent along with their insulated mats or air mattresses, on which sleeping bags are placed, food and utensil boxes, radio, stove, lamp if summer light is not enough, and scientific equipment, including computers, maps, and navigational and meteorological gear. Cooking is usually done while in the sleeping bag. Food today, even if ration packs are used, is much more appetizing and varied and less monotonous than in the past. The tent is warmed when food is prepared, and from solar heat on clear days. Water vapor is readily generated from breathing and cooking, as well as from clothing and footwear—damp from the perspiration of exercise—which are hung in the peak of the tent to dry. The moisture passes through a vent in the peak or condenses on the inner lining of the tent. Tent dwellers soon learn not to touch this lining to prevent showers of frost from descending on them. They also learn to store snow blocks for melting for water in between the two layers of the tent near the entrance to save going outside. Similarly, one learns to wear adequate clothing when one must go outside to attend to "calls of nature," as a tent can quickly "warm" relative to the outside temperature.

Household tasks such as dressing; removing frozen moisture from clothing, innersoles, and sleeping mats; melting snow for water (at least ten times the volume of snow is required to produce the volume of water needed); cooking meals and preparing drinks or soup to take in vacuum flasks while engaged away from campsite; maintaining radio schedules with main base; and recording scientific data are very time consuming, as it takes much longer to do things under the field situation. Attention must be paid to time, and a routine worked out, as it is very easy to become undisciplined.

Emergency equipment—depending on destination and pursuits—is carried by each party. Everyone depends on each other, and living so close for lengthy periods means each person gets to know the other well, both the positive and negative aspects. There tends to be great camaraderie. Behavioral effects of field living are important, and in little time people tend to become very efficient. This includes simple tasks such as filling vacuum flasks with boiling water each night so there is water to commence breakfast preparation the next morning. Ablutions in the field range from snow baths, teeth cleaning, and simple washing of face and hands to showers at fixed locations.

Food/Diet

As well as discomfort from cold, the nutrition of many of the early expeditions was inadequate in both calories and content such as vitamins. Supplementation from seal, penguin, and bird eggs was frequently the norm. In many instances eating fresh meat kept nutritional diseases such as scurvy at bay. As the food increased in variety, the vitamin and essential mineral content increased, and nutritional diseases became less common. By today's standards the food in the huts a century ago was limited, with few luxury items. Sledging rations in the field were even more spartan and monotonous, and prepared only on a Nansen-type cooker over a small stove. Pemmican—the composition of which varied, but tended to be dried meat with fat or lard, sometimes with added yeast extract—gave high caloric content and was the staple with biscuits, chocolate, and drinks such as cocoa.

Diets today match those of the country of origin, assisted by the facts that modern processing, packaging, and storage give much greater variety and that preparation is in the main by professional chefs who often have a rotation of rostered lay assistants to help. Dietary discretions of all types are accommodated at many bases. Fresh fruits and vegetables are limited in summer unless air supply is possible and absent in winter unless small quantities of salads are grown under hydroponic conditions. During winter, meat is usually frozen or tinned and vegetables are tinned, frozen, or freeze dried. Ration packs are still used today in the field by a number of nations and are high energy, but the variety is great and preparation made easier by use of microwaves at field bases. Many groups in the field eat food that differs little from that on stations, as supplies are regularly flown in. The diaries of early Antarctic explorers, especially those who had to survive against incredible odds, described vivid dreams of dining on fine food at fashionable restaurants as well as rescue fantasies. These men wrote of constant hunger, thirst, lack of sleep, and a monotony of occupation, companionship, and color.

Summer Season

Summer in Antarctica is the season of great activity. The return of the sun brings the wildlife to breed, aircraft break the silence of winter in September/October, and in the following months as the sea ice breaks up ships penetrate to coastal stations. Both bring large numbers of people subsuming the small, remote winter groups. Scientists engage in major programs, many of which are international; support personnel work at rebuilding, maintenance, and repair of stations; and thousands of tourists and adventurers visit. Below the Antarctic Circle, the midnight sun becomes a stimulus for frantic work and play. Twenty-four hours of sunlight can also cause insomnia, referred to as "big-eye." Aircraft and shipping bring a constant turnover of people in austral summer, as personnel strive to complete their programs before transport departs the continent in late February to April. Fresh fruit, vegetables, and supplies are as welcome as new faces. In this age of e-mail and satellite phones, mailed letters and parcels are still welcomed in summer as a connection with the outside world; mail and supplies cannot be delivered during winter.

Winter Season

With summer over, some bases close, while those remaining open during winter have their populations reduced by as much as 80%. As aircraft and shipping activity ceases, fieldwork decreases and the scientific program, apart from observatory functions, is much reduced. Human studies are best investigated during winter. Isolation is more intense and the social environment is very different from that in summer. Although life is less hectic, along with work, it can be boring and repetitive. Altered immune status has been found in those wintering in Antarctica, just as in other populations under stress.

Reports from Antarctic winterers suggest the occurrence of a "winter over syndrome." Symptoms include irritability, hostility, inability to concentrate, difficulty in memory, fugue states that are referred to as the "Antarctic stare" or "long eye," and insomnia. Considerable research has taken place during the past 50 years, but the etiology has not been identified; some psychiatrists and psychologists suggest that the "winter over syndrome" is not a pathological state but an adaptation to small numbers, confinement with the same associates and tasks, isolation from family and work colleagues, inability to leave the hostile environment, and the environment itself, whether cold or photoperiodicity. Not all personnel have the same experience during winter. Many investigations in Antarctica have assumed that the environmental stressors adversely affect physical and mental health. This is possibly due to the abundance of anecdotal reports. Blizzards, changes of temperature and light, and cosmic radiation have all been suggested as having a relationship with psychosomatic manifestations, but there is no scientific consensus. The majority of people adapt well, with the occurrence of psychological/psychiatric problems during the Antarctic winter low. To most, wintering in Antarctica is a very positive experience.

Community life is important in winter to cope with the reduced numbers of people and the added complexities of work. Subgroups are often formed, as staff members are drawn together because of similar work (scientists or nonscientists), social pursuits (drinkers or nondrinkers), and those in relationships (having a partner or not). Folklore, customs, ceremonies, and cultures have developed, with some behavior classed as bizarre by those outside Antarctica. To those in Antarctica it can be "normal." Morale is variable, ranging from "midwinter blues" to fluctuations due to work load, daylight hours, or specific events rather than season. There is no common pattern. Methods of facilitating adjustment to wintering are many and varied. Tolerance and humor are important individual characteristics, while social events, physical endeavors, and activities, such as station newspapers, all play a part. Groups who had husky teams were known to enlarge their human groups by the individual dogs' assuming human status. Food is most important, and those who eat well are generally happier than those who do not. Mutual dependence is universal in Antarctica and there is a unique spirit of camaraderie that extends beyond the national group, to be found between those from different nations who have wintered in Antarctica.

Returning Home

Returning home from Antarctica is a most provocative experience. There is a readjustment to sounds such as traffic noise, smells (especially of vegetation), rain, in some cases use of money, and to society, including family, friends, and work colleagues. Some would say it represents a retribalization from the microcosm of life in Antarctica to society at large.

Summary

Extreme cold, isolation, and long periods of daylight and darkness create challenges for those living in the Antarctic regions. Most people who spend time in Antarctica return home having had an enjoyable and positive experience, seeing their time on the harsh and icy but beautiful continent as stimulating and rewarding. Testimony to this is the large number of people who return for subsequent summer or winter sojourns as members of national research or tourist groups.

DESMOND J. LUGG

See also **Art, Antarctic; Australasian Antarctic Expedition (1911–1914); Aviation, History of; Base Technology: Architecture and Design; Base Technology: Building Services; Books, Antarctic; Clothing; Dogs and Sledging; Fiction and Poetry; Field Camps; Film; Health Care and Medicine; Music, Antarctic; Ponies and Mules; Scurvy; Tourism**

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MACARONI PENGUIN

The macaroni penguin, *Eudyptes chrysolophus,* is one of the largest of the six species of crested penguins. Adult macaroni penguins weigh 5–6 kg, there being variation among individuals from breeding localities. They are blue-black on their backs and white ventrally. Long golden-yellow feather plumes extend from the forehead along the sides of the head above the eyes, forming a broad, loose crest. The large bill is red-brown, eyes dull red, legs and feet pink.

Distribution

Macaroni penguins have a more southerly distribution than most other species of crested penguins, breeding between about latitudes 45° and 65° S in the western Indian (Heard Island and McDonald Islands, Îles Kerguelen, Îles Crozet, and Prince Edward Islands) and South Atlantic Ocean (Bouvetøya, South Sandwich, South Georgia, South Orkney, South Shetland, and Falkland groups of islands and in low numbers at islands off the Antarctic Peninsula). It also extends into the southeast Pacific Ocean along the coastline of southern Chile. The largest colonies are north of about 55° S. In the southwest Pacific Ocean, the macaroni penguin is replaced by the closely related and similar in appearance royal penguin, *E. schlegeli,* at Macquarie Island.

Macaroni penguins leave their breeding localities after moulting, but for many colonies, their at-sea distribution in the nonbreeding season is poorly known. It is thought that they remain in sub-Antarctic waters. Vagrants, mostly moulting immature birds, have been recorded in South Africa and Australia.

Annual Cycle

Macaroni penguins moult once each year, in autumn, when they replace all their feathers. At this time they are ashore for 3–4 weeks and do not feed, as they can not enter the water. Before moulting, they spend about 2 weeks at sea fattening up. Once the moult is complete, they go back to sea during winter to regain condition. In spring they return to their colonies to breed, males arriving at colonies about a week before the females. There is considerable synchrony in the timing of breeding and moult, and colonies are devoid of birds during winter.

After their arrival at colonies for breeding, both parents fast again for periods of 30–40 days. They remain at the nest site until about 8 days after the eggs are laid. The male then departs to sea for about 13 days, leaving the female to incubate the eggs. Soon after his return she departs, for about 10 days. She returns just before the eggs hatch. Both parents are at the nest for the first 2–3 weeks after hatching. The male guards the chick, while the female undertakes short feeding trips to provision it. Later the chick joins a crèche, at which stage both parents feed it, at first the female more frequently than the male, which has fasted a third time for several weeks. The incubation period lasts about 36 days, the fledging period about 60 days. Breeding birds depart on their premoult feeding trip soon after their chicks have left the colony.

Breeding and Survival

Macaroni penguins are colonial breeders, usually breeding in large colonies. They are monogamous, with often long-lasting pair bonds. Nests are on level or steep ground that frequently is devoid of vegetation because of trampling. The female forms the nest scrape, which is then lined by pebbles collected by both sexes.

Macaroni penguins lay clutches of two eggs. The interval between laying of the two eggs is 4–5 days. The first egg is on average 38% smaller than the second egg. It seldom survives, often being dislodged during nest scraping. Only one chick is typically reared to fledging.

Macaroni penguins are able to breed when 3 years old but may defer breeding until they are 8 years old. When food is scarce, substantial numbers of birds do not breed. Annual survival of adults is about 75%.

Food and Feeding

Macaroni penguins feed on euphausiids, amphipods, small fish, and cephalopods. Crustaceans dominate the diet fed to small chicks; larger prey may predominate in the diet of older chicks. Food is caught by pursuit diving. Birds dive to depths of less than 20 m at night, but to greater depths in the day, following the daily migrations of their prey towards the surface at night and away from it in daylight.

During incubation, both sexes undertake extensive foraging trips (at South Georgia on average about 375 km for females and 575 km for males) whereas, during chick rearing, trips are often shorter (at South Georgia about 60 km).

Population Size

Macaroni penguins are more numerous than any other crested penguin, numbering about 9 million pairs. The largest populations are at South Georgia (2.5 million pairs), Crozet (about 2 million pairs), Kerguelen (1.8 million pairs), Heard (about 1 million pairs), Prince Edward (300,000 pairs), and Bouvetøya (100,000 pairs) groups of islands.

Conservation Status

The macaroni penguin is classified as Vulnerable on the Red List of IUCN (The World Conservation Union), because the overall population appears to have decreased by at least 20% over a period of 36 years, equivalent to three generations. It is believed that the population at South Georgia probably halved after 1980. Competition between fur seals and macaroni penguins for food resources may increase as fur seal populations increase. The availability of food around colonies may be influenced by climate change and environmental perturbations.

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See also **Antarctic Important Bird Areas; Antarctic Peninsula; Birds: Diving Physiology; Bouvetøya; Crested Penguins; Crozet Islands (Îles Crozet); Fish: Overview; Gentoo Penguin; Heard Island and McDonald Islands; Kerguelen Islands (Îles Kerguelen); Macquarie Island; Prince Edward Islands; Skuas: Overview; South Georgia; South Orkney Islands; South Sandwich Islands; South Shetland Islands; Zooplankton and Krill**

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MACQUARIE ISLAND

Macquarie Island, a tiny piece of ocean floor tectonically uplifted above the surface of the Southern Ocean, is of importance to marine mammals, marine birds, and humans. To thousands of seals, penguins, albatrosses, petrels, and other sea birds, Macquarie Island is of crucial importance as the land on which they breed. To humans, when the island was first discovered in 1810, it was important as a source of wildlife to be exploited: for fur seal skins, elephant seal oil, and, later, penguin oil. Now the island has been recognised by humans as important in its own right, and is reserved as a World Heritage Area, a World Biosphere Reserve, and as the Macquarie Island Reserve, bounded to the east by the Macquarie Island Marine Park.

Macquarie Island, with Bishop and Clerk islets nearby to the north and Judge and Clerk islets to the south, lies in the vicinity of 158°55′ E, 54°30′ S, approximately 1500 km southeast of Tasmania and 1100 km southwest of New Zealand. Just north of the Antarctic Polar Front Zone, and exposed to the winds of the "furious fifties," the island has a cool, moist, windy, but equable climate. Mean surface 9 am air temperature is 5.0°C with seasonal variation of 3.4°C–7.2°C at sea level. Mean annual precipitation is 953 mm, falling as rain, mist, sleet, hail, or snow on approximately 313 days per year. Windspeed at 9 am averages 9.3 m s^{-1}. Extensive cloud cover means that sunshine hours average 2 hours per day. Evidence for climate change is seen in the slightly warmer temperatures and lower precipitation during recent decades.

The elongate island, 34 km long and varying between 2 and 5 km wide, comprises an undulating plateau at 200–300 m above sea level (asl), bounded by steep coastal slopes. The highest point is Mount Hamilton, 433 m asl. At the northwest corner of the island, a marine-cut terrace supports an extensive mire locally known as "the featherbed."

Macquarie Island is the above-ocean part of the Macquarie Ridge Complex, uplifted by plate-boundary processes between the Pacific and Australian tectonic plates. The southern two-thirds of the island is pillow basalts, with an exposed ophiolite complex in the north. The island has been above the ocean surface for approximately 700,000 years, and is still rising at an average rate of approximately 0.8 mm per annum. The present size and shape of the island is a result of interplay between tectonic uplift, sea-level changes, and coastal erosion as uplift proceeds. Cobble-strewn raised beaches up to 280 m asl provide evidence that all parts of the island have, at some past time, been at sea level during the uplift process. These same well-preserved cobbled raised beaches are consistent with glaciation never having been part of the island's geomorphic processes. Instead, landforms have been shaped by faulting processes, by erosion, by wind and water, and by interaction of physical processes with vegetation in terracing hillsides, damming lakes, and forming mires.

The island's vegetation is treeless, with closed herb vegetation on the coastal slopes dominated by tussocks of the grass *Poa foliosa* (up to 1.5 m tall) and the megaherb *Stilbocarpa polaris* (known since sealing days as Macquarie Island cabbage and used then as an antiscorbutic addition to diet). The megaherb *Pleurophyllum hookeri* (a rosette-leafed maroon-flowered daisy) and short tussocks of the grasses *Agrostis magellanica* and *Festuca contracta* and the sedge *Luzula crinita* form closed vegetation cover on many parts of the plateau. The endemic cushion plant, *Azorella macquariensis,* dominates the open vegetation, feldmark, on much of the plateau, important in the vegetation banking the gravel-surfaced terraces that form a striking component of the landscape. Bryophytes (mosses and liverworts) are important components of the vegetation, particularly in the feldmark and in the extensive mires on the plateau and the featherbed.

The vascular flora includes five species of ferns and fern allies, and some thirty-nine species of flowering plants, of which three are endemic (*Azorella macquariensis, Corybas dinemus,* and *Puccinellia macquariensis*) and three considered alien (*Cerastium fontanum, Poa annua,* and *Stellaria media*). The bryoflora includes eighty-eight species of mosses and fifty-one species of liverworts, of which one moss species is considered alien *(Funaria hygrometrica)*. From the island's rocky shores, 103 species of marine macroalgae, including the large bull kelp, *Durvillaea antarctica,* have been recorded.

Populations of previously exploited marine mammals have recovered well. Elephant seals and three species of fur seals (New Zealand, Antarctic, and sub-Antarctic) now breed on the island, with interbreeding between the fur seal species. Populations of king penguins and the endemic royal penguins *(Eudyptes schlegeli)* have also recovered well from exploitation, and continue to expand on the island. Rockhopper penguins and gentoo penguins breed on the island in significant numbers. Four species of albatrosses (wandering, grey-headed, black-browed, and light-mantled sooty), two species of giant petrels (northern and southern) and seven species of smaller petrels breed ashore.

Two species of endemic terrestrial vertebrates have become extinct since humans started visiting Macquarie Island: a flightless parakeet, *Cyanorhamphus novaezalandiae erythrotis,* and a flightless rail, *Rallus* *philippensis macquariensis*. During the same period a larger number of alien terrestrial vertebrate species has arrived and become established: rabbits, cats, ship rats, house mice, and wekas. Each has had significant impacts on aspects of the island's ecosystem: rabbits on terrestrial vegetation, the others on burrow-nesting birds. Management programs have successfully eradicated cats and wekas, and reduced the population of rabbits. Ongoing control or eradication of rabbits, rats, and mice is a significant challenge facing the management of this sub-Antarctic island reserve.

The numerous freshwater lakes and streams on the island support a range of aquatic biota including flowering plants, bryophytes, green algae, diatoms, cyanobacteria, and lower invertebrates (protozoa, rotifers, tardigrades, nematodes, flatworms, segmented worms, freshwater crustaceans). Like the flowering plants, both freshwater and terrestrial invertebrates include a number of endemic species. Nine species of terrestrial invertebrates are considered to be resident alien.

The first time Macquarie Island was used for serious scientific purposes was during the Australasian Antarctic Expedition (AAE, 1911–1914), when a party of five under the command of George F. Ainsworth established a base to serve as a meteorological station and wireless-relay point between the expedition's main base at Commonwealth Bay and Australia. Significant biological, geological, and survey work was also carried out. When the AAE members departed, the station was maintained briefly by the Commonwealth Meteorological Service. As during the AAE, since 1947 a scientific research station has been maintained at the northern end of the island, at which biological, geological, climatological, and upper-atmospheric research are conducted. For its scientific interest and for its wild beauty, Macquarie Island has become of considerable interest to ecotourists. As at all visited sub-Antarctic and Antarctic sites, the ecosystem on Macquarie Island is at risk from human visitation, and management includes careful quarantine, in order that the characters for which the island is valued are maintained.

PATRICIA SELKIRK

See also **Algae; Antarctic Fur Seal; Australasian Antarctic Expedition (1911–1914); Black-Browed Albatross; Conservation; Crested Penguins; Gentoo Penguin; Grey-Headed Albatross; King Penguin; Light-Mantled Sooty Albatross; Liverworts; Mosses; Nematodes; Northern Giant Petrel; Penguins: Overview; Polar Front; Pollution; Rotifers; Sealing, History of; Southern Elephant Seal; Southern Giant Petrel; Sub-Antarctic Fur Seal; Tardigrades; Wandering Albatross**

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MAGNETIC STORM

A magnetic storm is an interval of large nonsecular variation of the geomagnetic field, usually on a global scale. The term *magnetic storm* is attributed to Alexander von Humboldt in 1808. Subsequently, many definitions of magnetic storm have been proposed and used. Commonly, a magnetic storm is defined as an interval of extreme perturbation of a local or global measure of the geomagnetic field, usually sustained over a few hours to days. Typically, *extreme* may mean less than about 1% likelihood of occurrence and corresponds to a peak perturbation of the total geomagnetic field of up to 10%. More recently, the magnetic storm has also been defined as a particular pattern of variation of the Disturbance storm time (Dst) index, which is a spatial and temporal average of the northward geomagnetic field variation at low latitude. The characteristic pattern of Dst variation usually shows three phases: (1) Initial phase—an interval of variable duration of Dst above its baseline, often commencing with a sharp rise known as storm sudden commencement. (2) Main phase—a rapid fall of Dst to a minimum after about 10 hours. (3) Recovery phase—slow recovery of Dst towards the baseline over about 2 days. In this definition, magnetic storms are classified according to their strength, measured by the minimum Dst value attained. A typical classification scheme is weak ($-30 \geq$ Dst > -50 nT), moderate ($-50 \geq$ Dst > -100 nT), strong ($-100 \geq$ Dst > -200 nT), severe ($-200 \geq$ Dst > -350 nT), and great (Dst ≤ -350 nT) storms. Under this definition, a magnetic storm is not a particularly extreme event since over 20% of Dst values are less than -30 nT.

Magnetic storms are the result of a stronger than usual interaction between the solar wind (the outflow of charged particles from the sun into interplanetary space) and the Earth's magnetosphere (the comet-shaped region of near-Earth space dominated by the geomagnetic field). This is typically associated with fast-moving magnetic plasma structures from the sun's corona known as coronal mass ejections. The frequency of magnetic storms varies with the 11-year solar cycle—a periodic variation of the number of sunspots on the sun. The frequency ranges from about twenty moderate and stronger storms per year at solar minimum to about forty-five storms per year at solar maximum.

Magnetic storms are also associated with intense aurora, extending to abnormally low latitudes. In Antarctica, storm-time aurorae are likely to be most prominent at locations farthest from the South Magnetic Pole such as the Antarctic coast between Halley and Syowa stations and the Antarctic Peninsula. There can actually be a paradoxical reduction in magnetic and auroral activity in regions closer to the Pole.

Magnetic storms have been identified as a natural environmental hazard that can adversely affect radio communications, electrical power grids, satellite operations, and astronauts. Thus it is desirable to forecast the occurrence of a magnetic storm from its birth on the sun to its impact at Earth, but such forecasts are not yet reliable.

Mervyn Freeman

See also **Antarctic Peninsula; Aurora; Geomagnetic Field; Magnetosphere of Earth; Plasmasphere; Solar Wind; South Pole**

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MAGNETOSPHERE OF EARTH

The Earth's magnetosphere is that region of space in which the large-scale motion of electrically charged matter is dominated by the Earth's magnetic field. It is formed by the interaction of the solar wind with the magnetic field of Earth. (The solar wind is the stream of charged particles emitted from the Sun and streaming towards the Earth. It is the ultimate source of energy driving polar phenomena such as the aurora and magnetic storms.) The matter within the magnetosphere is in the plasma state, consisting of positively charged ions and negatively charged electrons. The plasma may be regarded as an electrically conducting gas of very low density.

In a magnetic field, charged particles move easily along the direction of the field; their motion perpendicular to the field is limited. The long period waves known as Alfvén waves are also constrained to move parallel to the magnetic field. (Alfvén waves are waves that exist in a magnetised plasma at very low frequencies. They transport energy precisely parallel to the magnetic field. They are an important mechanism for transmitting information about changes in the magnetospheric configuration from one point to another.) At low latitudes the Earth's magnetic field lines do not extend far into space; at high latitudes they extend deep into space. The properties of the particles and waves travelling along these field lines are determined by the properties of those parts of the magnetosphere that are threaded by the field lines. When they arrive in the upper atmosphere the particles cause phenomena such as the aurora. The waves are associated with disturbances of the magnetic field and the electric field in the ionosphere. The polar regions are therefore the only regions where ground-based study leads to an understanding of the properties of the outer magnetosphere. The Antarctic continent is thus a window into geospace (which is the region of space surrounding the Earth).

The Earth's Main Field

As a first approximation, in the immediate neighbourhood of the Earth itself, the Earth's magnetic field

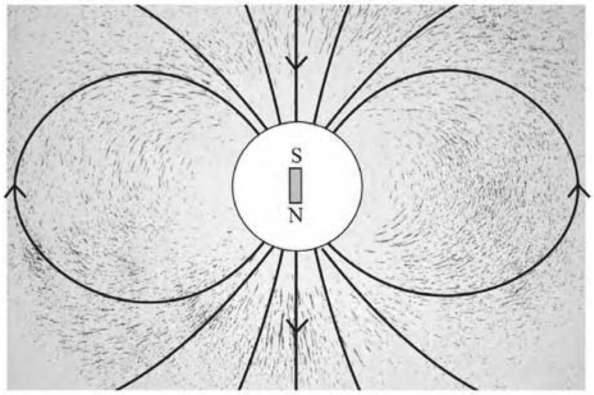

Figure 1 Geometry of a dipole field. This shows a photograph of iron filings under the influence of a magnetic field. Superimposed on it a set of field lines have been drawn. These are lines representing the direction of the magnetic field at each point. Conventionally, in a careful representation, they are drawn as closer together when the field is strong and further apart when it is weak. In the diagrams here the geometry makes this difficult and we have drawn the field lines to represent direction only and do not intend their separation to suggest a magnitude.

resembles that of a bar magnet (a magnetic dipole) at its centre. The actual sources of the field are currents flowing in the molten core of the Earth and driven by the Earth's rotation. The axis of the equivalent dipole is tilted with respect to the axis of rotation of the Earth. The field of such a bar magnet can be visualised by sprinkling iron filings on a sheet of paper covering the magnet. If the paper is tapped gently, the iron filings tend to align themselves along the field.

A magnetised compass needle placed in the Earth's magnetic field tends to align itself with the direction of the field. The end that points towards the north is conventionally labelled the north or north-seeking pole of the magnet. Like poles of two magnets repel each other and unlike poles attract. Thus the equivalent bar magnet producing the Earth's field actually has its south-seeking pole at the northern end as illustrated.

The magnitude of the Earth's field decreases strongly as the inverse cube of the radius so that its value at a distance of 5 Earth radii is less than one percent of its value at the surface. The predominant sources of the field at less than about 4 Earth radii are the internal currents. Before the era of space exploration it was frequently assumed that this was the case out to all distances. As this field decreases the fields of distant current sources external to the Earth become important. These currents arise from the interaction of the charged particles of the solar wind and the magnetic field.

Formation of the Magnetosphere

Impact of the Solar Wind on the Earth

The Sun continuously ejects matter in the plasma state. This plasma is called the solar wind. It consists predominantly of positively charged protons and electrons with a smaller component of heavier ions, mainly helium. The solar wind speed is typically 300 to 500 kilometres per second and its density is a few particles per cubic centimetre, far more tenuous than the best vacuum that can be obtained in the laboratory. It is possible to show that, if a magnetic field exists in the plasma, the magnetic field lines follow its motion as if they were frozen into it. Magnetic fields originating in the Sun have an energy density that is small compared with the kinetic energy density of the solar wind plasma. This magnetic field is, therefore, carried along with the solar wind. It is known as the interplanetary magnetic field (IMF). As the solar wind approaches the Earth it encounters a region where the magnetic field is large so that the field energy density is comparable with, or much larger than, the density of energy associated with plasma motion. Here the plasma motion is strongly affected by the magnetic field. The consequence is that we can divide geospace into two regions. In one the behaviour is dominated by the solar wind flow; in the other it is dominated by the Earth's magnetic field. There are various physical models, described next, that help in understanding how this occurs.

Closed Magnetosphere

As a first approximation we can neglect the magnetic field in the solar wind and regard it as a conducting gas. As the solar wind approaches the Earth the magnetic field increases rapidly. Near the Earth the magnetic field energy density is much larger than the energy density associated with plasma motion, which is therefore controlled by the geometry of the magnetic field. The consequence is that the motion of the solar wind is affected by the Earth's magnetic field. A boundary is formed between the region dominated by the Earth's magnetic field and the solar wind. The geomagnetic field is confined to a cavity, known as the magnetosphere. The boundary of this cavity is called the magnetopause. At the magnetopause there is equilibrium between the pressure of the flowing plasma of the solar wind on the outside, and the effective pressure, arising from magnetic forces, on the inside. The situation is complicated by the fact that the speed of the solar wind relative to the Earth exceeds the speed of sound in the

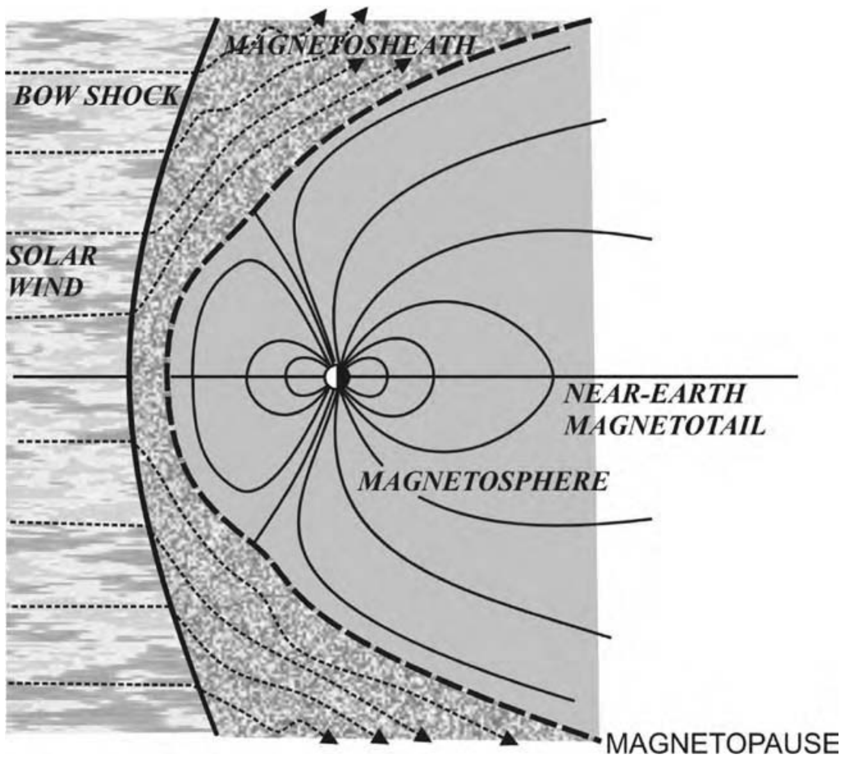

Figure 2 Closed magnetosphere. This figure shows a cross section of geospace in a plane (the noon-midnight meridian plane) containing the Earth-Sun line and the Earth's dipole axis. The bow shock is represented by a heavy line and the magnetopause by a heavy dashed line.

solar wind plasma. This leads to the formation of a shock wave like the bow wave of a ship, or the shock in front of a supersonic aircraft. This is called the bow shock. On the sunward side of the shock the solar wind flows undisturbed: between the shock and the magnetopause its flow is disturbed by the presence of the magnetosphere; it is diverted to flow round the magnetopause. On the Sun-Earth line the distance from the shock to the magnetopause is about 2 Earth radii (12,800 km) and the distance of the magnetopause from the centre of the Earth is about 10 Earth radii (64,000 km).

In this closed magnetosphere model, neither the bow shock nor the magnetopause would be observable from ground-based instruments in Antarctica. Nevertheless, physical processes in the region strongly affect the particles entering the magnetosphere and the magnetic fields within the magnetosphere, leading to many phenomena, such as the aurora and various magnetic disturbances that are observed in the polar regions.

Magnetic Reconnection

The situation becomes more complicated if we take into account the interplanetary magnetic field carried by the solar wind. Suppose, for example, that it is directed in a southerly direction. Then, when the solar wind encounters the magnetopause, the magnetic field is in the opposite direction to the magnetic field just inside the magnetopause. This is represented in Figure 3A, in which PQ represents the surface dividing the two oppositely directed fields. On this surface the magnetic field is zero and it is therefore called a neutral sheet. The inward flow from the Sun means that such a situation is unstable and tends to relax to the situation shown in Figure 3B. Here there is a line perpendicular to the page on which the field is zero—the neutral line, represented by the point O in the middle of the shaded region. Here two magnetic field lines cross, suggesting that the field points in two directions at once! This is not the absurdity it seems, because it is here that the magnitude of the field is zero and the direction in which it points is meaningless. In the shaded region surrounding O the picture of frozen-in field lines does not hold: outside this region it does. Plasma is flowing into this region from the solar wind. If it is not to accumulate it must flow outwards along some other path. Calculation shows that it flows inwards from the solar wind and from the magnetosphere, and outwards along the magnetopause, as indicated by the white arrows. It flows inwards over a large area and

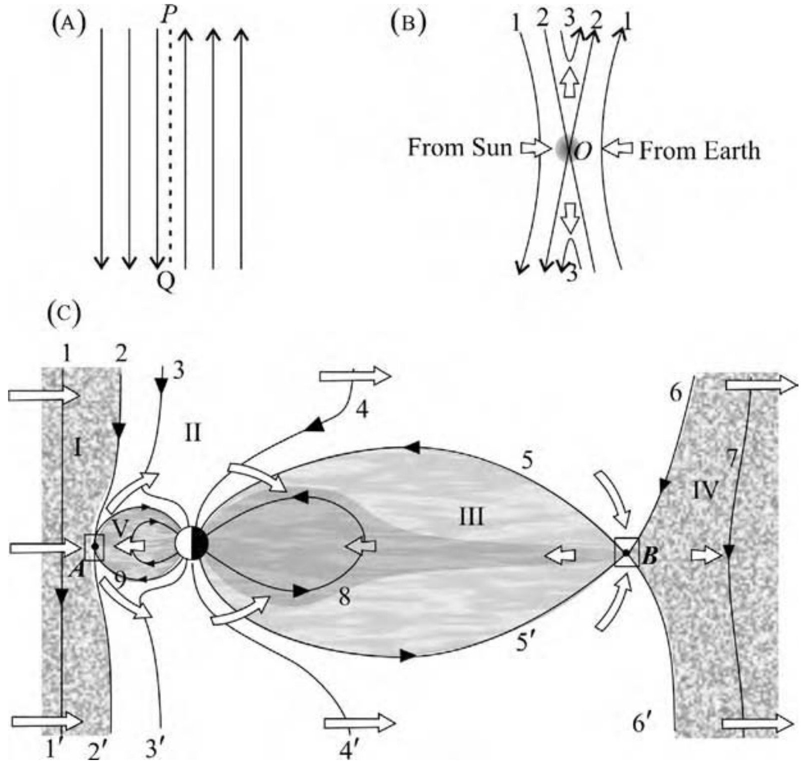

Figure 3 Field line merging: magnetic reconnection (A, B) and open magnetosphere (C).

outwards over a small one, so it is accelerated by this process.

Outside the shaded region the magnetic field lines are frozen into the plasma as described previously. If one follows the motion of the plasma from the solar wind, as it passes through the shaded region, the associated field lines are reconfigured. It is as if, at *O,* they are cut and rejoined in a different configuration. This process is known as magnetic reconnection or magnetic merging.

Open Magnetosphere

Figure 3C illustrates the noon-midnight cross section of the magnetosphere. The Sun is far to the left of the diagram and the solar wind flows from the left. The IMF is southward. Conditions in the small rectangle *A* then favour reconnection. Let us follow a field line in the solar wind region (the shaded region labelled I) at position 1 as the solar wind proceeds towards the Earth. The ends of this field line are either connected to the Sun, or meet each other in the distant solar wind to form a closed loop: they are not connected to the Earth. At a later time this field line has reached position 2 and passes through the reconnection region *A*. The reconnection process requires that, at the same time, plasma is flowing into *A* from the front of the magnetosphere (the shaded region labelled V). At the same time as the solar wind field line reaches the reconnection region *A* a field line from within the magnetosphere reaches it as well and is reconnected as described above. At a later time the two parts of the reconnected field line have reached position 3 and 3′. The field lines in the unshaded region II are carried back as the solar wind flows past the magnetosphere. These field lines are connected at one end to the Earth and at the other to the solar wind; they can be said to have "one foot on the ground." As the plasma flows further the field lines become more and more stretched out, being dragged into a long tail. In the process the magnetic field becomes more and more distorted. Magnetic forces affect the plasma flow. At great distances the pressure is large enough to bring the field lines together at *B* where there is further reconnection as illustrated. The field line at 4 is carried to position 5 and 6, and is reconnected to the field lines in position 5′ and 6′. After reconnection part of the plasma flows on into region IV to rejoin the solar wind, while the remainder flows back towards the Earth through region III, past the Earth on either side, and into region V to take part in the reconnection process at *A*. This process of circulation is driven by the solar wind and is known as magnetospheric convection.

The process described here is greatly idealized. The IMF is seldom directed exactly southward. If, however, it has a southward component, then, as it is dragged past the Earth, reconnection takes place at some point on the sunward side of the magnetosphere and the process is qualitatively similar. If, on the other hand, it has a northward component then reconnection does not in general occur in this way, although there may be reconnection far back on the tail lobes. The process has also been idealized as happening steadily and uniformly. In reality the solar wind is gusty; the reconnection region is not stable. The process is very dynamic and can be better described as patchy and variable with our description representing an average picture.

The Antarctic and Arctic regions are ideally situated for observing these processes. It will be noted that magnetic field lines originating at high latitudes in Antarctica are directly connected to the solar wind. Those at lower latitudes may stretch into the deep tail. The convection processes in deep space map along the magnetic field lines to show effects in the Antarctic upper atmosphere. Energetic charged particles are constrained to move along the field lines and may be precipitated in the upper atmosphere where they collide with neutral atoms and raise their energy. When these atoms relax to their unexcited states they release this energy in the form of light, giving rise to the aurora.

The Regions of the Outer Magnetosphere

The processes described previously cause geospace to be divided into a number of regions, in each of which the magnetic field geometry and the particle populations are different. This is illustrated in Figure 4. This diagram is more nearly to scale than the previous figures. Again the solar wind blows from the left. Figure 4A shows the noon-midnight meridian, Figure 4B the equatorial plane, and Figure 4C a cross-section perpendicular to the Sun-Earth line on the plane *AB*. The various plasma regions are described next and can be located by referring to the diagram.

Magnetosheath. After the solar wind passes through the bow shock its density and pressure are increased and its velocity decreased. It flows past the magnetosphere. As a result of the passage through the shock it tends to be more turbulent. This region of turbulent flow at relatively small velocity is called the magnetosheath. It is confined to the region between the bow shock and the magnetopause. The plasma in the magnetosheath originates from the solar wind.

Cusp. In the closed magnetosphere of Figure 2 the magnetic field is confined to the interior of the magnetopause. None of the field lines are connected to the magnetosheath or the solar wind. The outermost field lines are parallel to the magnetopause. There is a critical field line that emerges from the polar regions on the day side and connects with these outermost field lines. At the point where it reaches the magnetopause the magnetic field is zero and its direction is indeterminate. At this point there is no bar to plasma entering the magnetosphere from the magnetosheath. In the more realistic case of Figure 4 this critical field line is connected to the solar wind and is surrounded by a roughly conical region of field lines that are connected to the magnetosheath and solar wind. This region is known as the polar cusp or simply the cusp. The plasma in the cusp originates both from the solar wind and from the Earth's atmosphere. Plasma from the atmosphere is lost upwards by a process akin to evaporation. The upward flowing atmospheric plasma is know as the polar wind. Energetic solar wind plasma can enter the cusp and be precipitated in the upper atmosphere. The cusp intersects the ionosphere in the northern and southern polar regions. Ground-based observations in Antarctica continue to lead to improved understanding of physical processes occurring in the cusp.

Regions of the magnetotail. The stretched out tail-like region drawn out from the magnetosphere behind the Earth is known as the magnetotail. The boundary region threaded by field lines originating in the cusp is known as the plasma mantle. These field lines are draped over the outer part of the magnetotail, their configuration determined by the details of solar wind flow. There are stretched-out portions of the magnetotail on either side of the equatorial plane in which the plasma density is relatively low. These are known as the tail lobes. In the southern lobe the magnetic field points away from the Earth and the northern towards it, as indicated in Figure 4C by the symbols $\otimes$ and $\odot$. At the equatorial plane there is an increased density in the region known as the plasma sheet. The equilibrium is maintained by currents flowing in the directions indicated by arrows in Figure 4C. These currents arise as a consequence of gradients in the pressure and self-consistently provide a magnetic force that balances the forces arising from the gradients of the plasma pressure.

These regions all map along the field lines to the polar caps in the Antarctic and Arctic. Ground-based observations of magnetic fields, energetic particles, and plasma velocity in the upper atmosphere have led to better understanding of physical processes in the magnetotail.

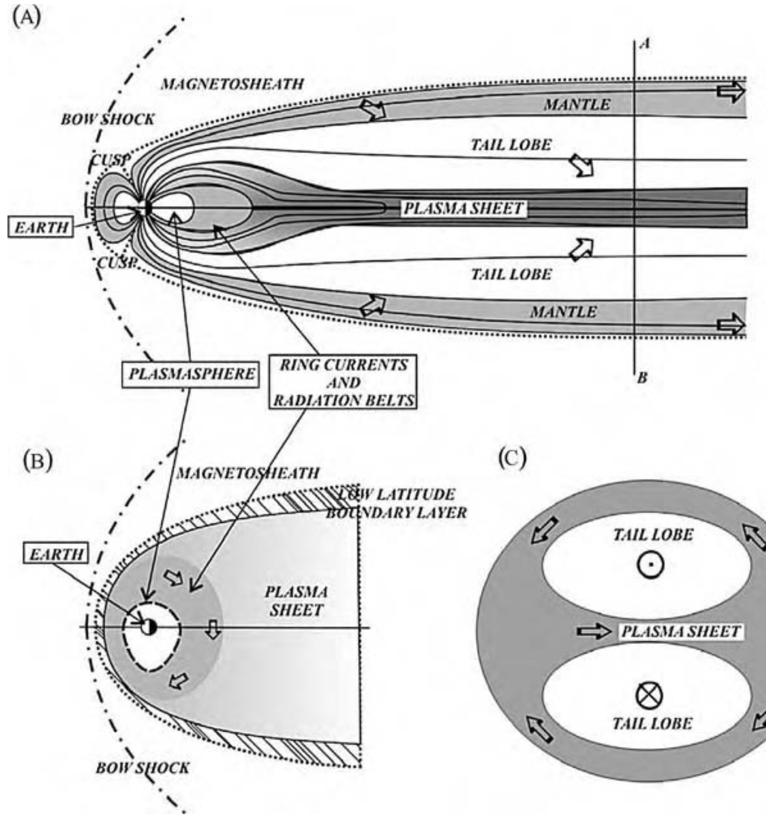

Figure 4 Open magnetosphere.

Regions of the Inner Magnetosphere

Ring current. In Figure 4A the plasma sheet is located in a region where the field lines are so stretched out that they point either directly away from or towards the Earth. As we move towards the Earth we encounter a region where the field lines are closer to the shape of the dipole field lines of Figure 1. In this region the plasma sheet merges into a plasma region known as the ring current region. This region surrounds the Earth. It is indicated by the shaded region shown in the equatorial plane in Figure 4B. It is called the ring current because the increasing inward gradient of plasma pressure leads to a westward current encircling the Earth, as indicated by the arrows in Figure 1B. This current leads to a small reduction of the Earth's magnetic field. This effect is seen at lower latitudes than in Antarctica. On the inner edge of the ring current region the pressure gradient is in the opposite direction and there is an eastward current, but this is small so that the overall effect is of a westward current. The ring current is variable. At times of low magnetic activity it may be negligible: at disturbed times its effects on the magnetic field at the ground are significant.

Radiation belts. In the same region as the ring current there are two regions of much more energetic charged particles. These are the inner and outer radiation belts. They were first observed by James van Allen using one of the earliest space probes and are also known as the van Allen belts.

Plasmasphere. As we move closer to the Earth we encounter a region where the density of plasma rises rapidly. It becomes more than a thousand times greater than in the region of the radiation belts. This region is shown unshaded in Figures 4A and 4B. It consists of plasma originating from the Earth's atmosphere, and constrained by the Earth's magnetic field to rotate with the Earth. Its outer boundary is called the plasmapause. The plasmapause is the boundary between the region where the geometry of the magnetic field constrains the plasma to rotate with the Earth and the region where magnetospheric convection (see later discussion) allows exchange of plasma with the solar wind. The plasmapause maps to the ground along magnetic field lines at a geomagnetic latitude of about 60°. Because of the tilt of the magnetic dipole this magnetic latitude crosses the Antarctic continent in the South Atlantic sector. On the other side of Antarctica this magnetic latitude lies in the South Pacific and Indian Oceans. As a result the stations well-equipped to observe the plasmapause are those such as Halley and Sanae, lying near the Greenwich meridian. The USA station Siple, now closed, played a very important part in the understanding of plasmapause phenomena in the 1970s and 1980s.

Magnetospheric Convection

The previous discussion indicates that there is a steady flow of solar wind plasma past the magnetosphere. At the reconnection regions there is an interaction between plasma within the magnetosphere and the solar wind. There is a motion of plasma out of the magnetosphere in the region *A* of Figure 3 and a motion into the magnetosphere in region *B*. This implies a circulation of plasma, known as plasma convection. We study this process and its effects in the Antarctic upper atmosphere in more detail.

Figure 5 shows various aspects of the convection process. Figure 5A shows a portion of Figure 3. The shaded region shows the magnetic field lines that originate in the Antarctic region and connect with the solar wind after reconnection in the region *A*. There is a similar region in the Northern Hemisphere. In this region the solar wind can be regarded as a conducting fluid moving through the illustrated magnetic field. When a conductor moves through a magnetic field it generates an electric field. This is the same process as that which drives an electric generator in a power station. In the power station, energy is extracted from whatever fuel is used to drive a motor that rotates conducting coils in a magnetic field, thus generating an electric field; in the solar wind a fraction of the energy associated with its motion is extracted to generate a field that is perpendicular to the plane of the diagram, and directed downwards.

The charges move freely along the magnetic field lines so there is no electric resistance parallel to them. As a result the electric field maps down to the upper atmosphere. Figure 5B is a map of this electric field in the Antarctic ionosphere. The shaded circular region is the region within which the magnetic field lines connect the Earth to the solar wind. The full lines show the direction of plasma flow in the ionosphere.

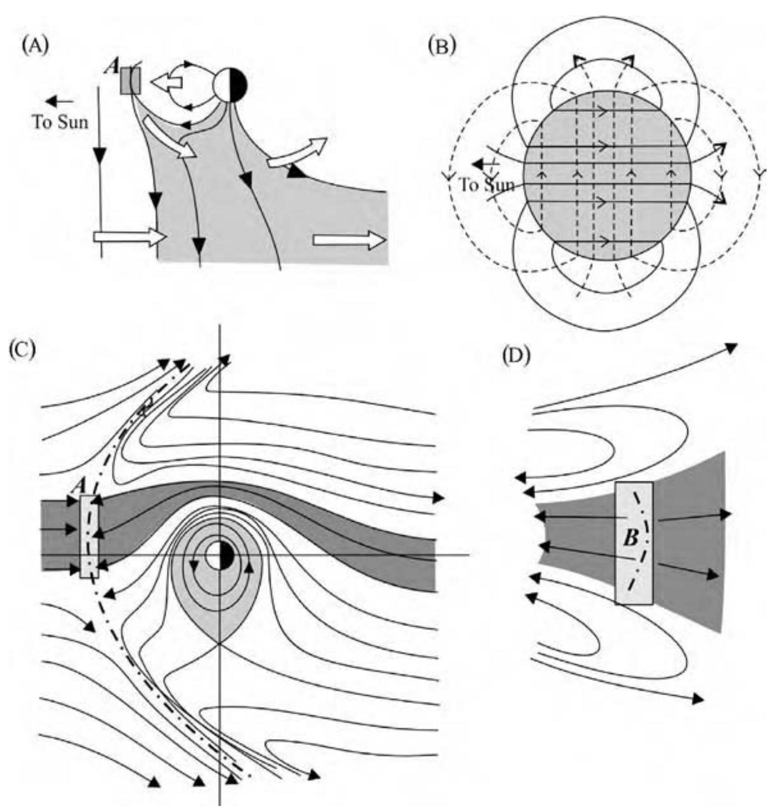

Figure 5 Magnetospheric convection. (A) Noon–midnight meridian over Antarctica. (B) Antarctic polar cap. Full lines represent direction of the flow in the upper ionosphere; dashed lines represent the direction of the accompanying electric field. (C) Motion in the equatorial plane. (D) Motion far down the tail in the equatorial plane.

The dashed lines show the direction of the electric field. Within the shaded area the plasma flows away from the Sun. The total voltage across this region arising from the electric field is large. During times of strong magnetic disturbances it may exceed 100,000 volts. At less-disturbed times it is a few tens of thousands of volts. There is a return flow outside the polar cap region in the direction shown, resulting in the formation of two cells of oppositely circulating flow. Currents in the lower ionosphere due to differential motion of positive and negative charges are associated with this flow. They give rise to magnetic perturbations of the ground. This picture is highly idealised to the case where the interplanetary magnetic field is southward. The Earth's rotation causes further modification. In other cases the reconnection region forms on different parts of the magnetosphere and leads to modified convection patterns in which the convection pattern may change and, indeed, the number of cells may increase.

Figure 5C shows the lines along which plasma flows in the equatorial plane near Earth, and Figure 5D shows the flow in this plane far down the tail. The magnetic field lines are perpendicular to the plane of the paper. The darker shaded regions contain plasma that emerges from the reconnection region *B* and enters the reconnection region *A*. The magnetopause is represented by a chain line. At the magnetopause, plasma inside the magnetosphere may be dragged along by the magnetosheath plasma by a viscous interaction. The viscous force is an additional driving force for convection. The relative importance of reconnection and viscous drag has been the subject of controversy. There is reasonable consensus that reconnection is far more important. Viscosity is not thought to provide more than about 15% of the drag. The paler shaded region represents the plasmasphere. Within this region the field lines remain approximately dipole shaped and rotate with the Earth's rotation. Outside this region the field lines are carried to the magnetopause and are either reconnected with solar wind field lines or dragged back by viscous interaction. Since the field lines inside the plasmapause remain connected to the atmosphere for long times this region is filled with ions of atmospheric origin, and the plasma is much denser than outside it, where the plasma is a mixture of ions of solar wind and atmospheric origin. This convection process can be observed in the Antarctic ionosphere. A map of the convection may be obtained by the international SuperDARN chain of radars. In the southern hemisphere these are located at Halley, Sanae, and Sjowa on the Antarctic continent, on Kerguelen Island, and in Tasmania. They are capable of measuring the plasma flow.

The Dynamic Magnetosphere

It must be emphasised that this steady state situation, described previously, is an idealised picture of a dynamic and rapidly changing situation. The structure of the magnetosphere is determined by the solar wind, which is variable and gusty. Solar flares can eject large quantities of high-speed plasma. Coronal mass ejections can occur in the absence of flares. The solar wind velocity, density, and magnetic field vary as conditions on the Sun change. The response of the magnetosphere is not instantaneous but depends on a variety of physical processes. These processes are important for the understanding of the space weather environment in which satellites and spacecraft operate. Observations on the Antarctic continent are crucial to this understanding.

Magnetic Storms

When sudden increase in the density and velocity of the solar wind, arising from a coronal mass ejection or similar phenomenon, arrives at the Earth, it leads to an immediate compression of the sunward side of the magnetosphere. This implies a sudden increase in the magnetic field. Information about this increase is transmitted throughout the magnetosphere by Alfvén waves in a matter of minutes. The resulting sudden increase in the magnetic field seen on the ground is called a sudden commencement. After the initial increase a number of effects lead to energization of magnetospheric particles and a variety of currents flowing within the magnetosphere. The electric field arising from the increased dynamo effect at the poles increases dramatically. The cross-polar potential difference may exceed 100 kilovolts. The initial increase of magnetic field may last for several hours. It is generally followed by a disturbed period, the main phase, during which the ring current, associated with the drift of energetic particles, is enhanced in the region near four Earth radii. This enhanced current provides an additional magnetic field that is directed northwards, roughly parallel to the Earth's axis. This leads to a reduction of the magnetic field at lower latitudes. This is followed by a recovery, at first rapid, then slower. During the recovery phase of the storm the energetic particles are slowly lost through precipitation into the atmosphere and charge exchange with neutral particles. The whole process typically lasts for several days.

Such storms can lead to surges in power lines (not a problem in Antarctica) and may cause severe damage to satellites and spacecraft through bombardment by energetic particles. Other effects are radio communication blackouts and severe magnetic disturbances, which may affect activities such as geophysical surveys. The understanding and prediction of the effects of magnetic storms is an important objective of Antarctic ground-based studies of the magnetosphere.

Magnetospheric Substorms

The magnetospheric substorm provides some of the most spectacular effects of magnetospheric activity in the auroral region. It is associated with dramatic auroral displays, and strong magnetic and electrical disturbances. At one time it was thought that magnetic storms were essentially composed of overlapping substorms, hence the name. While many substorms may take place during a magnetic storm, other effects that are not associated with substorms also occur. The aurorae associated with substorms were the subjects of the first studies. The name auroral substorm was applied to these phenomena. Later it was recognised that the auroral phenomena were part of a complex physical process involving nonauroral effects, and the name magnetospheric substorm was adopted.

A substorm arises as a consequence of stored magnetic energy in the magnetotail being released in a fairly local segment of the magnetosphere and energising charged particles, which in turn provide the enhanced currents and auroral effects associated with the substorm. The precise physical mechanisms are the subject of controversy. During a substorm, magnetic field lines that are stretched into the tail undergo a sudden collapse to a more dipolar shape over a relatively narrow longitude segment. In this process, particles are energised and injected into the ring current region. Their precipitation into the upper atmosphere leads to auroral displays; the enhanced ring current leads to magnetic disturbances. The pattern of convection over the polar caps is strongly affected. The substorm is preceded by a growth phase during which energy is being fed into the magnetotail. It is followed by an expansion phase during which the energy is released, and finally by a recovery phase. The expansion phase during which the most intense effects are observed lasts about half an hour. The whole process takes place within a few hours. While substorms are common during magnetic storms, they may also occur during otherwise quiet times.

Aurora

During a substorm there is a rapid collapse of part of the magnetotail. Field lines that were previously stretched out become less stretched. The plasma attached to the field lines is compressed and energised. Large currents flow along the field lines and through the ionosphere. As a consequence, these instabilities can allow a potential difference above the ionosphere along a field line. This accelerates and energises particles further. They may collide with neutral atoms in the upper atmosphere, raising them to larger energy levels. When they relax to the ground state they emit photons of visible light, leading to the formation of the aurora.

Magnetospheric Oscillations

The magnetosphere is very dynamic, changing on many timescales. For timescales that are long compared with those characteristic of the plasma medium the plasma motion is well described by magnetohydrodynamics. In this approximation, the characteristic waves are Alfvén and magnetosonic waves. When these have periods of a few minutes, their wavelengths are comparable with the scale of the magnetosphere itself. As a consequence they can set the magnetosphere oscillating in a variety of modes of oscillation. Such waves are an important mechanism for transferring energy between the magnetopause and the ionosphere. They are observed on the ground as oscillations of the Earth's magnetic field or as oscillations in the convection velocity of the ionosphere.

A. D. M. Walker

See also **Aurora; Auroral Substorm; Geomagnetic Field; Geospace, Observing from Antarctica; Ionosphere; Magnetic Storm; Magnetospheric Convection; Plasmasphere; Solar Wind**

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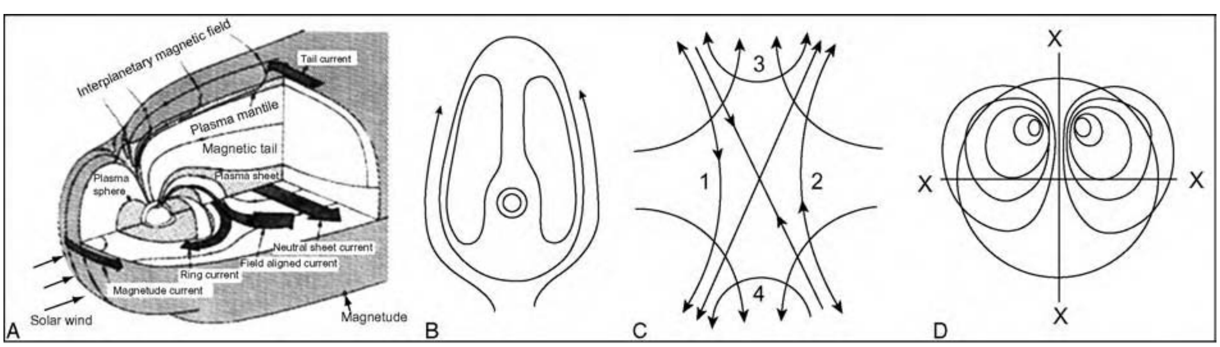
MAGNETOSPHERIC CONVECTION

The large-scale flow of rarefied plasma in the Earth's magnetosphere "is quite analogous to thermal convection" (Gold 1959); therefore, the term "convection" is commonly used to describe large-scale circulation inside the magnetosphere caused by the interaction of the solar wind (SW) with the geomagnetic field. This circulation results in the zero sum of electric fields $\mathbf{E} + \mathbf{v} \times \mathbf{B} = 0$, or $\mathbf{v} = \mathbf{E} \times \mathbf{B}/B^2$. Assuming that the electric field $\mathbf{E}$ is a gradient of a scalar function $\mathbf{E} = -\nabla \boldsymbol{\Psi}$, where $\boldsymbol{\Psi}$ is an electric potential imposed from the SW, then $\mathbf{v} \times \mathbf{B} = \nabla \boldsymbol{\Psi}$. The latter is a convective circulation of geomagnetic field lines in the crossed $\mathbf{E}$ and $\mathbf{B}$ fields. By analogy with the thermal convection in a nonconductive fluid $\partial \mathbf{B}/\partial t = \nabla \times (\mathbf{v} \times \mathbf{B})$, which means that the magnetic field is tied (frozen-in) to the corresponding plasma flow.

Two major forces control the large-scale magnetospheric convection: (1) transfer of a viscouslike momentum from the SW to adjacent regions of the magnetospheric tail (Axford and Hines 1961), and (2) front-side reconnection between the interplanetary magnetic field $\mathbf{B}_{\mathrm{IMF}}$ and geomagnetic field $\mathbf{B}_{\mathrm{geo}}$ (Dungey 1961). The SW flow around the magnetosphere carries magnetospheric "outer edge" plasmas with frozen-in geomagnetic field tubes tailward along the flanks; then returns these tubes with their plasma content by means of a sunward flow, skirting into the regions closer to the Earth. This generates a dawn–dusk electric field, $\mathbf{E}_{\mathrm{qv}} = -\mathbf{v}_{\mathrm{SW}} \times \mathbf{B}_{\mathrm{geo}}$, where $\mathbf{v}_{\mathrm{SW}}$ is the SW velocity in the magnetosheath: a region between the bow shock and the magnetopause. A similar flow pattern is formed in the magnetosphere due to the reconnection processes between the (oppositely directed) magnetic fields over the magnetosphere's front (sunlit) side, when the IMF is oriented opposite (southward) to the general (northward) direction of the geomagnetic field. This also imposes the interplanetary electric field $\mathbf{E}_{\mathrm{IMF}} = -\mathbf{v}_{\mathrm{SW}} \times \mathbf{B}_{\mathrm{IMF}}$ onto the magnetosphere in the dawn–dusk direction, which is then projected downward into the ionosphere along the geomagnetic field lines.

Magnetospheric convection in turn induces motions in the high-latitude ionosphere through linkages along the geomagnetic field lines, which carry a load of field-aligned currents and electromagnetic waves from the magnetopause down to the ionospheres of both the northern and southern polar caps. The magnetospheric convection produces the ionospheric plasma circulation in a form of two-cell convection pattern. This pattern maps down the magnetospheric "outer edge" field tubes flow over the geomagnetic pole in the antisunward direction and the return flow in the sunward direction along the lower-latitude, auroral zone.

Magnetospheric convection is a major driver of geomagnetic activity; it increases with faster SW and



(A) Regions and currents in Earth's magnetosphere. (B) Viscous convection pattern. (C) Magnetic merging (reconnection) at X-line. (D) Convection in the polar ionosphere.

larger southward IMF, causing more rapid stirring of the magnetospheric plasma. This triggers more charged particles to precipitate into the polar ionospheres and increases cross-polar electric fields and corresponding ionospheric currents. This activity is seen from the Earth's surface and space as magnificent aurora that illuminates the northern and southern polar skies.

VLADIMIR PAPITASHVILI

See also **Aurora; Geomagnetic Field; Ionosphere; Magnetosphere of Earth; Solar Wind**

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MARGINAL ICE ZONE

The marginal ice zone (MIZ) forms the transition zone between the open, ice-free ocean and the continuous ice cover of the interior icepack. Ice conditions in the MIZ are continuously shaped by wave action, affecting both the growth and the breakup of ice floes. Average floe size increases across the MIZ, with the smallest floes (less than 1 meter diameter) at the edge. The MIZ is bounded seaward by the open ocean. The interior boundary is most commonly defined as the point at which incoming waves and ocean swell have diminished to the point that they have negligible influence on the character of the ice cover, or, alternatively, where ice divergence or concentration (the percentage of the sea surface covered with ice) is the same as that of the interior icepack. Wave penetration depends on the amplitude and period of the incident waves and on the nature of the ice cover, so that the width of the MIZ varies both spatially and temporally. This distance is typically about 100–300 km. Both broader and much greater in extent than its Arctic counterparts, the Antarctic MIZ is by far the largest in the world. In mid-winter it forms a continuous band stretching some 20,000 km around the continent. The total winter extent may be several million km^2, or perhaps 20% of the total sea-ice covered area. In areas of narrow pack ice extent such as in East Antarctica, the influence of ocean swell can extend almost to the continent. In summer, as the ice retreats to a narrow strip along the coast, the MIZ can be considered to comprise almost the entire width of the icepack.

The MIZ is dominated by strong spatial gradients. Seaward of the ice edge the ocean is relatively warm and moderates the near surface air temperature. To the south, the ice insulates the ocean, so that surface temperatures can drop well below freezing within a few tens of kilometers of the ice edge. There is, then, a tenuous balance between freezing and melting in the vicinity of the MIZ. Ice conditions may vary substantially with the position of the ice edge. The frequent passage of storms along the edge brings alternating incursions of warm air from over the ocean and outbreaks of cold air from over the ice, affecting the local position and shape of the ice edge and modifying freeze and melt cycles. The MIZ itself influences its local environment. Complex atmosphere-ice-ocean interactions associated with the strong gradients of the MIZ can generate a variety of mesoscale (having scales of tens to several hundred kilometers) phenomena that affect winds, currents, and ice drift. The ice responds rapidly to these forcings so that the MIZ is constantly changing in position, shape, and ice conditions.

While the ice edge may occasionally form a sharp transition from open water to close-packed ice, more commonly a diffuse edge forms where small floes and broken ice are aggregated into one or more long, linear bands. These are typically 1 kilometer or more wide and some 10 kilometers long, though a range of sizes occur. The bands may be separated from one another by several kilometers, and can range over many tens of kilometers before a more continuous ice cover is encountered. Mesoscale features are common along the ice edge. Meanders may form various promontories or embayments. Ice-edge eddies can form cusped protrusions, often giving the appearance of breaking waves in satellite imagery. Another common feature is long tongues of ice that jut out into open water, often with two counterrotating vortices at the head giving a mushroom-like appearance.

Ice Types and Characteristics

In winter, the ice edge advances at a rate greater than the northward drift speed of individual floes, so that the advance is primarily due to formation of new ice at the edge. Everywhere in the circumpolar Antarctic, the ice edge is exposed to the wide fetch and rough seas of the Southern Ocean, so the MIZ is continuously buffeted by significant wave action and swell.

Ice formation therefore takes place almost exclusively via the frazil-pancake cycle. Freezing begins through the nucleation of loose crystals known as frazil ice. Constant motion due to wave action prevents the consolidation of new ice crystals into an ice sheet. As freezing progresses, the frazil crystals form a loose soupy suspension known as grease ice that damps out the short capillary waves, giving the surface a matte appearance. As this soup thickens the frazil crystals will agglomerate into small pan-shaped discs of ice known as pancakes. As they are tossed about by the waves, cyclic collisions of individual pancakes promote adhesion of more frazil crystals and growth of the pancakes, and eventual consolidation of individual pancakes into large floes.

Seaward of the main ice edge, there are often one or more discrete bands of thin pancakes. At the main edge, the ice cover typically consists of thin pancakes 10–20 cm in diameter of moderate concentration embedded in an expanse of grease ice. Centimeter scale waves are damped by the viscous frazil slurry, but waves of several meters in wavelength may still be present. With increasing depth, the ice concentration increases as the pancakes gradually increase in size to 1–3 meters in diameter, reaching thicknesses of about 0.3–0.5 m. These larger pancakes will effectively attenuate all waves with wavelengths comparable to their size so that slow, rolling swell of several tens of meters or more in wavelength dominates. With deeper penetration, the individual pancakes begin to fuse together to form floes of gradually increasing diameter. As the floes grow, they will attenuate progressively longer wavelength swell. The transition to consolidated pack ice happens quite abruptly (diameters increasing from 20 m to greater than 200 m in about 25 km are typical) as even the longest waves are damped to the point that they can no longer break up vast floes (several kilometers in size).

As frazil and pancake ice form, a fraction of the ocean surface remains ice-free and is continuously exposed to cold air, maintaining a large heat flux from the ocean to the atmosphere and a high rate of ice formation. This permits rapid thickening of the ice cover even under relatively high temperatures. Pancakes only a few days old may reach thicknesses of about 50 cm. This is particularly important since, once a consolidated ice cover has formed, the ice insulates the ocean from the atmosphere and ice growth proceeds at a much slower rate. In much of the Southern Ocean, the weak surface stratification allows substantial heat from warmer, deeper water to reach the underside of the ice, thus inhibiting further growth. Despite the relatively narrow width of the MIZ, it is responsible for generating a significant fraction of the total pack-ice volume.

Several other processes contribute to ice thickening in the winter MIZ. As the ice concentration in a field of pancakes increases, individual pancakes will raft over one another due to wave action or compaction of the ice cover, effectively doubling or tripling the ice thickness. Enhanced thickening occurs when seawater and frazil crystals are thrust onto the surface of pancakes as they are jostled by waves or rafting, where they can more rapidly freeze. If snow is present on the surface, this wetting will create a slush that, upon freezing, forms ice of granular texture known as snow ice. It is unclear how important snow ice accretion is in the MIZ. Despite the young ice, snowfall is greater at the ice margin than deeper in the pack, so snow depths of several centimeters are common within the inner MIZ. Total ice thickness at the inner edge of the MIZ generally falls between 0.2 and 0.5 m. Congelation ice (ice formed during downward growth of crystals due to a vertical temperature gradient through the floe) is rare, but is occasionally found at the base of some floes.

The ice characteristics during the summer are quite different. Growth of new ice ceases and ice is advected from the south to melt at the retreating ice edge. Much of this ice will have developed away from the edge and so will have a structure typical of the interior pack, where congelation ice makes up roughly half of the total thickness. Some of the ice may be multiyear ice, having survived the previous summer melt season. Floes typically have angular shapes due to wave-induced fracture. Larger floes are interspersed with brash—small, irregular bits of ice broken from larger floes.

Wave–Ice Interaction

The greatest influence on the development and character of the ice margin is the action of ocean waves and swell. Waves control both the initial formation and consolidation of the ice, and the breakup of larger ice floes. This interaction is complex, as it is a function of ice thickness, floe size, and the incoming wave spectrum. Ice cover acts as a low-pass filter, so that shorter period waves are rapidly attenuated within a few kilometers of the ice edge. Long wavelengths, on the other hand, can penetrate loose-packed ice almost unimpeded. Swell of noticeable amplitude with a wavelength of several hundred meters has frequently been observed hundreds of kilometers from the ice edge.

The floe size and swell amplitude are tightly coupled. Wave energy attenuates exponentially with depth of penetration into the pack, generally increasing with increasing wave period and ice thickness. If the floes are much smaller than the wavelength, they will act as individual rafts riding on the swell, and damping is minimal—the wave does not "see" the floe and passes beneath it with little loss of energy. This accounts for the very deep penetration of swell into the Antarctic MIZ, where small pancake ice causes minimal decay of the long swell that often exists there. The mass of the ice does modify the propagation of the wave, however. At the ice edge, the incident wave is refracted perpendicular to the ice edge. The wavelength in the ice is less than in open water, decreasing with increasing ice thickness. The decrease in wavelength causes a steepening of the swell.

As the floe size approaches the wavelength of the swell, the floe will respond by bending. This forms an ice-coupled wave known as a flexural gravity wave. In this case, the wave is partly reflected from the floe. In a field of many floes, reflections from each floe will effectively scatter the wave energy so that the energy in the forward propagating wave attenuates rapidly. This occurs as the pancakes consolidate into floes of diameter of the same order as the size of the swell. The attenuation due to scattering increases with ice thickness.

Flexural gravity waves can cause the breakup of consolidated ice deep into the interior icepack. Large amplitude swell will strain a large ice floe due to bending. The maximum strain typically occurs between 20 and 100 m from the ice edge, increasing with the swell period and ice thickness. If the strain is sufficient to cause fracture, a new ice edge will be exposed to the swell, and the breakup can continue progressively deeper into the pack until the swell is diminished by scattering and viscous damping. The breakup of ice more than 500 km from the ice edge has been observed. The floes nearer the edge will be broken into still smaller floes as they are exposed to shorter period waves than ice deeper in the pack. The production of smaller floes alters the attenuation rate of the waves, allowing the shorter period waves to penetrate deeper, where they will break the ice into still smaller floes. There is thus a tendency toward a continuous gradation of increasing floe size with distance into the MIZ. The distribution is seldom uniform at any given location. Varying swell and collisions break some floes apart and create brash, and new pancakes may form in between the large floes, so that a broad range of floe sizes (typically 1–100 m) and thicknesses (typically 0.1–0.7 m) can occur.

The propagation of swell in the MIZ has been observed in high resolution synthetic aperture radar satellite imagery. As the change in wavelength upon entering the ice depends on ice thickness, there is an exciting possibility for the extraction of ice thickness information from space. This has been hampered by the lack of an adequate theory for the propagation of waves in a realistic MIZ, but it has shown promise for estimating the thickness of frazil-pancake ice.

Atmosphere-Ice Interaction

The sharp discontinuity between ice-covered and ice-free seas and the strong atmospheric temperature gradient across the MIZ play an important role in processes at the ice edge. The wind stress (the frictional force exerted by the wind on the surface) is greater over the rough, rubbly fields of pancakes and broken ice than over the ocean. This increases atmospheric turbulence and thickens the atmospheric boundary layer and surface winds. More importantly, it causes the ice to drift more rapidly than the ocean in response to the wind. These conditions can create a very different response of the MIZ depending on the prevailing wind direction.

Under on-ice winds, the action of both winds and waves will compact the ice. The locally increased wind stress over the pancake zone causes ice convergence. As loose pancakes have little resistance to compression, rafting of pancakes is common. Warm air incursions are often associated with stratus cloud formation as the moist air is cooled.

During off-ice winds, the ice often breaks up into a series of ice bands oriented perpendicular to the wind. The ice at the edge is generally rougher than in the interior pack due to the upturned edges of the pancakes. The wind will exert more force on these floes, so that they drift at greater rate than the rest of the icepack, and the MIZ will diverge creating small patches of open water. Within these patches, short-period wind waves will develop. The reflection of these waves from the ice floes causes a wave radiation pressure force on the floes that will push the band further from the main icepack, thereby increasing the expanse of open water. The increased force on the edges of the band due to waves compresses the individual floes into a tight band. As these bands drift seaward they will move into warmer water and melt, both cooling and freshening the upper ocean. The bands thus play a role in speeding the advance of the freezing ice edge.

Strong off-ice winds can create atmospheric roll vortices aligned along the direction of the flow. These are long, helical vortices that give rise to parallel lines of convergence at the surface, and divergence aloft. The surface convergence can herd ice into long streamers that run perpendicular to the direction of the ice edge bands. Along the lines of divergence, long, linear cloud bands may form as rising, moist air condenses. These "cloud streets" are a ubiquitous feature of the MIZ during strong off-ice flow.

For wind parallel to the ice with the ice to the left, the temperature gradient from the air over the ocean to the ice will be greatest, creating a strong boundary layer front—a sharp boundary between air masses of differing properties confined to the lower atmosphere. A pronounced cloud band is often associated with such a front. The thermally induced pressure gradient can create an along-edge, jet-like wind. An off-ice component, or "ice-breeze," akin to the sea-breeze familiar along coastlines at lower latitudes, can also develop. As the jet follows the ice edge, rotational circulation will develop in any meanders in the edge position. This circulation can form vortices that, under favorable conditions, may develop into polar mesocyclones (i.e., short-lived intense cyclonic systems with a typical scale of a few hundred kilometers). Through a similar process, the zonal asymmetry of the ice edge position contributes to the genesis of larger scale cyclonic storms.

Ice-Ocean Interaction and Mesoscale Features of the Ice Edge

Ocean fronts—regions of strong gradients in temperature and salinity—are often associated with MIZs. These are important for two reasons. First, they form a physical barrier to the advance of the ice edge, as ice advected across the front will melt rapidly as it drifts into warmer waters. Second, instabilities in along-frontal flow can generate meanders and eddies that influence the morphology of the ice edge. The ice acts a passive tracer as its drift mirrors that of the underlying ocean circulation, producing an array of features easily observable in satellite imagery. Eddies moving seaward carry ice into warmer water, while others carry warm water deeper into the ice. The net effect is to enhance the rate of melting at the ice edge.

In the Antarctic, the main polar front lies north of the furthest extent of sea ice, so that unlike Arctic MIZs, the influence of fronts is limited. Such processes are restricted to regions such as Drake Passage and the Scotia Sea where sharp frontal structures do exist in the vicinity of the winter ice edge and eddies have been widely observed.

In summer, melting ice will cool and freshen the surface waters north of the retreating ice edge. The contrast between this low density meltwater and surface waters to the north forms an ice-edge front. The density gradient across the front can also generate a current flowing parallel to the front known as an ice-edge jet. Instabilities in these currents may also generate eddies. Such fronts have been observed in the Ross and Weddell Seas, although with only weak frontal currents.

The extent to which either process of ice-edge eddy formation occurs in the Antarctic is unknown. Nevertheless, mesoscale ice-edge features are common in satellite imagery. Many of these features might also be caused by the complex wind driven interactions that occur along the ice edge. There is some evidence that some mesoscale features at the ice edge during the summer may be caused by ocean eddies associated with the Antarctic Slope Front.

Ecology of the Ice Edge

The MIZ has an ecological importance far beyond its limited size. During the melt season, fresh water input from ice melt leaves a stably stratified water column behind the retreating ice edge. The stratification confines phytoplankton to the well-lit surface waters, encouraging the development of highly productive ice edge blooms. It is believed that ice algae may provide a seed stock for ice edge blooms as they are released into the ocean from melting ice, as species in the blooms are often similar to those found in the melting ice. The ice edge also appears to be important to other organisms. Large krill swarms have been observed just inside the ice edge. Seabirds, seals, and whales have all been observed in increased numbers near the ice edge.

TED MAKSYM

See also **Atmospheric Boundary Layer; Eddies in the Southern Ocean; Ice–Atmosphere Interaction and Near Surface Processes; Pack Ice and Fast Ice; Polar Lows and Mesoscale Weather Systems; Polynyas and Leads in the Southern Ocean; Sea Ice: Microbial Communities and Primary Production; Sea Ice Types and Formation; Southern Ocean: Fronts and Frontal Zones; Tides and Waves; Zooplankton and Krill**

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MARIE BYRD LAND, GEOLOGY OF

Marie Byrd Land is the large region within West Antarctica that borders the southern Pacific Ocean and eastern Ross Sea. Marie Byrd Land supports the northern part of the West Antarctic ice sheet, which is seated within a vast intracontinental rift that separates West Antarctica from the continental shield of East Antarctica. The predominant rock types exposed in coastal outcrops, narrow mountain ranges, and isolated nunataks are igneous and metamorphic. Consequently, the bedrock holds a wealth of information about geological processes that take place at depth below the Earth's surface. Moreover, since the crystalline bedrock is quite resistant to weathering and glacial erosion, the glacial landforms in Marie Byrd Land—horns, arêtes, whaleback ridges, and cliff-rimmed cirques—preserve a record of glacial advance and retreat of the West Antarctic ice sheet.

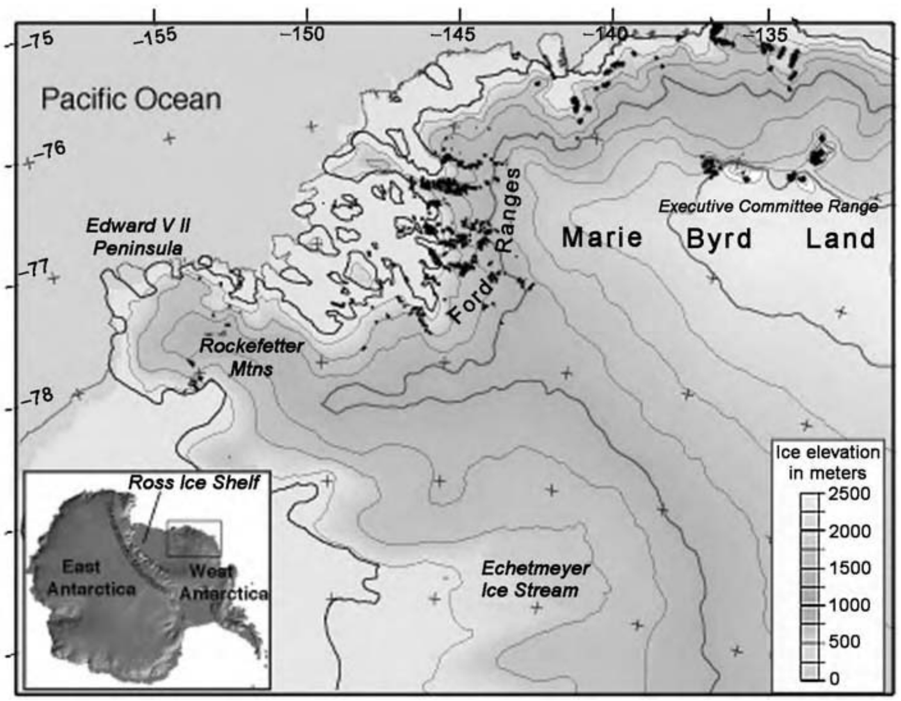
Plutonic and metamorphic rocks comprise the Ford Ranges and Rockefeller Mountains in western Marie Byrd Land, together with isolated ranges and scattered bedrock exposures along the coast, further east. Plutonism and metamorphism occurred at intervals from 375 to 98 Ma. However, the magnificent summits of the interior parts of Marie Byrd Land, rising to elevations of 3400 meters or more, are volcanic in origin. The isolated volcanoes and linear chains of volcanic summits are comparable in scale to features in the Cascade chain in North America. Previously nearly covered by the West Antarctic ice sheet, the ice-carved coastal landforms and big volcanoes have been exposed by deglaciation and lowering of the ice sheet, which commenced 10,400 years ago and continues today.

Plate Tectonic Setting

Marie Byrd Land's geological history is distinct from that of East Antarctica, and also differs from that of other geological provinces in West Antarctica. For example, Precambrian rocks are not known in Marie Byrd Land, and the Beacon Supergroup, the renowned sedimentary succession capping the Transantarctic Mountains, is nowhere found. Moreover, the timing and sequence of magmatism in Marie Byrd Land differs from that of Thurston Island or the Antarctic Peninsula, its nearest neighbors. Consequently, Marie Byrd Land is classified as a tectonic terrane: a fault-bounded block within Earth's crust that is made up of different geological units than neighboring tectonic blocks. Marie Byrd Land is one of four terranes that comprise West Antarctica. Discrete terranes commonly develop along subduction zones, or convergent margins, where oceanic crust converges with and sinks beneath continental crust. This is the case for Marie Byrd Land, which formed along the convergent margin of the Gondwana supercontinent. Materials of oceanic or magmatic arc character and sedimentary rocks derived from continental sources comprise the modern-day bedrock.

During early Paleozoic time, the margin of Gondwana underwent deformation and metamorphism due to convergence between tectonic plates, and experienced magmatism associated with subduction of oceanic crust. Mountain belts and magmatic arcs formed along the margin of Gondwana, and as they underwent erosion, they provided voluminous sediments that were transported and deposited along the extensive Paleozoic coastal margin. Marie Byrd Land was situated closer to East Antarctica at that time, and it received sediments from the mountains of the Ross Orogen. Intermittent subduction and magmatism continued in to the Mesozoic Era. Then, approximately 100 Ma, tectonic convergence gave way to extension and rifting of the continental crust.

A contemporary question in Marie Byrd Land geology is whether mantle plumes—upwellings of hot, rising material from deep within Earth—have played a role in the geological events of Mesozoic and Cenozoic time. The interplay of volcanism and glaciation is also of great interest. Marie Byrd Land's volcanoes arose 30 Ma, during the earliest stages of continental glaciation on the Antarctic continent. The coexistence of active volcanoes with the active West Antarctic ice sheet creates an opportunity to address questions about the onset of continental glaciation and the fluctuations in ice sheet volume during glacial cycles.



Marie Byrd Land supports the northern part of the West Antarctic ice sheet, which is seated within a vast intracontinental rift that separates West Antarctica from the continental shield of East Antarctica.

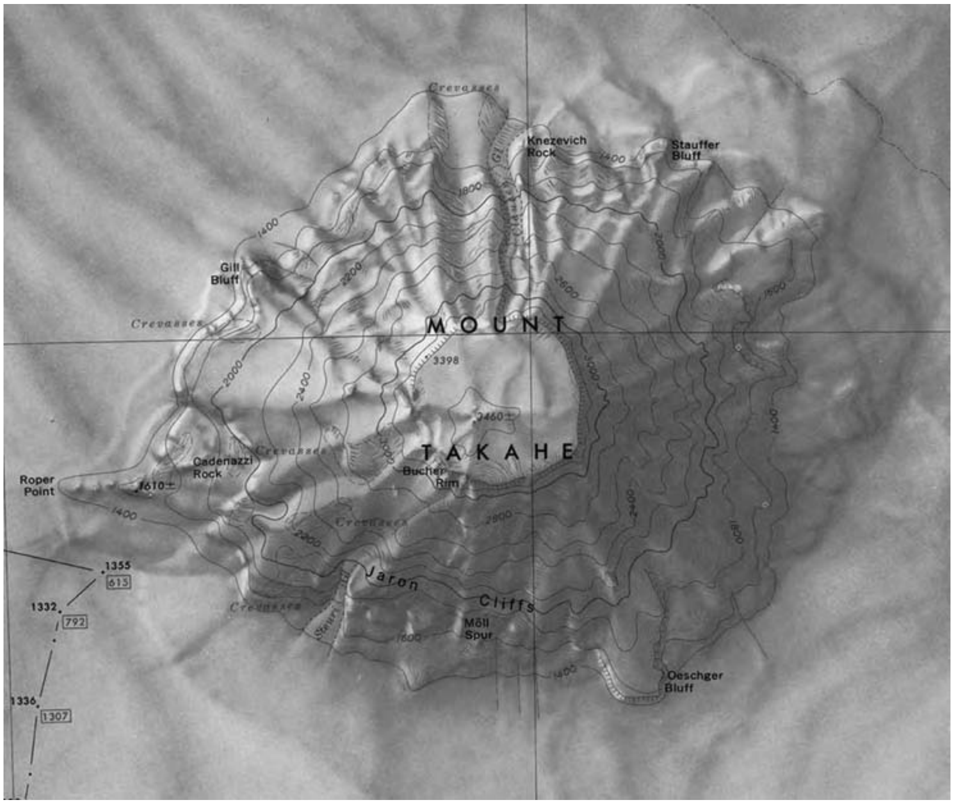
Geological History

Metamorphic and plutonic rocks of Cambrian to Cretaceous age comprise most of the mountain ranges and isolated nunataks near the Marie Byrd Land coast. These rocks provide a record of subduction along the margin of Gondwana in early Paleozoic and late Mesozoic time Volcanoes are the prevalent features in the interior of the terrane, and these have an alkaline chemistry, an indication that the volcanism, active from Oligocene (30–28 Ma) to Recent time, arises from depth in the Earth's mantle. Although no rocks of Precambrian age (>540 million years) are known, the isotope geochemistry of lower crustal xenoliths, or solid fragments plucked from depth by erupting magmas, suggests that Precambrian crust does underlie or adjoin the Marie Byrd Land terrane. Since the fossil record in Marie Byrd Land is meager, nearly all geochronological information for the terrane comes from isotopic mineral ages obtained from plutonic, volcanic, and metamorphic rocks. The mineral zircon is commonly used to determine the age of rocks and timing of events. Zircon forms as a crystal in igneous rocks, and upon erosion can become part of a sedimentary rock, where it is very resistant to weathering and chemical breakdown.

The sequence and timing of geological events determined for Marie Byrd Land are:

1. Sedimentation in early Paleozoic time, and formation of the oldest exposed rock unit, the Swanson Formation.
2. Deformation and metamorphism due to convergence along the Gondwana margin. Swanson Formation was folded into kilometer-scale folds and metamorphosed at low metamorphic grade.
3. Plutonism due to subduction of oceanic crust beneath the Gondwana margin. Ford Granodiorite plutons intruded the Swanson Formation.
4. Crustal stretching and thinning of Marie Byrd Land crust, accompanied by granitic plutonism. The Byrd Coast Granite was emplaced.
5. Alkalic volcanism from 30 Ma to Recent, with construction of large volcanoes.

The oldest rock formation in Marie Byrd Land, the Swanson Formation, is an immature sedimentary unit made up of greywacke and argillite. The Swanson Formation was deposited in early Paleozoic time, and preserves clear sedimentary layering and clastic textures that indicate deposition in a deep orogenic basin with a vast sediment supply. Detrital zircon grains within Swanson Formation suggest that the clastic materials were eroded from the early Paleozoic Ross Orogen of northern Victoria Land (Antarctica) and/or the Lachlan Orogen of Australia (Pankhurst et al. 1998). A subset of the zircons originally crystallized



The magnificent summits of the interior parts of Marie Byrd Land are volcanic in origin. Eighteen large volcanoes and diffuse smaller centers comprise the central Marie Byrd Land volcanic province. The volcano summits of the interior parts of Marie Byrd Land reach elevations as high as 4285 meters. Mount Takahe, shown here, rises to an elevation of over 3400 meters.

within granites of c. 500 Ma age, and another is of 1.1 to 1.2 Ga age. The granites were uplifted and eroded to provide sediment that accumulated in the Swanson Formation and other sedimentary formations in western New Zealand, Australia, and northern Victoria Land. The detrital zircon grains provide a "fingerprint" for the common source for the zircons and indicate that sedimentation occurred upon a continuous active margin of the Gondwana supercontinent.

At convergent tectonic margins, deformation and metamorphism typically occur, and those processes have affected the Swanson Formation. The Swanson Formation was folded into kilometer-scale, upright folds and was metamorphosed at low grade by 450 Ma. Presence of chlorite, a metamorphic mineral, gives the Swanson Formation a dark green color.

Plutonism began in Marie Byrd Land 375 Ma, with intrusion of Ford Granodiorite. The granodiorite has a calc-alkaline chemistry that indicates the presence of a subduction zone along the Gondwana margin during late Paleozoic time. The Swanson Formation–Ford Granodiorite association in western Marie Byrd Land has correlatives in the Paleozoic rocks of western New Zealand, northern Victoria Land (Antarctica), and Australia (Bradshaw et al. 1997), and is termed the Ross province (Pankhurst et al. 1998).

During the Mesozoic Era, subduction-related plutonism continued, but shifted to central and eastern Marie Byrd Land, where a magmatic arc developed (Mukasa and Dalziel 2000). Central and eastern Marie Byrd Land, with a Mesozoic record of arc magmatism, is termed the Amundsen province, and has geological affinities with eastern New Zealand, Thurston Island, and the Antarctic Peninsula.

About 100 Ma, in Cretaceous time, the Marie Byrd Land terrane underwent rifting and magmatism induced by the breakup of the Gondwana supercontinent. Intrusive rocks provide the record of this event, also. These are the Byrd Coast Granite in western Marie Byrd Land and mafic dikes intruded throughout the terrane. The plutonism coincided with stretching and thinning of the Earth's crust between East and West Antarctica, and formation of the Ross Sea portion of the West Antarctic rift system. The thinned continental crust subsided below sea level.

Fire and Ice

Volcanism in Marie Byrd Land began 36 Ma (Wilch and McIntosh 2000), and explosive eruptions continued until as recently as 7500 years ago (Wilch et al. 1999). Eighteen large volcanoes and diffuse smaller centers comprise the central Marie Byrd Land volcanic province. The volcano summits reach elevations as high as 4285 meters in the interior parts of Marie Byrd Land.

The cause of Marie Byrd Land volcanism is under debate. The alkaline geochemistry of the volcanic rocks is consistent with a rift or with a "plume" setting for volcanism. Consequently, one hypothesis, based on observations within Marie Byrd Land, is that a mantle plume, associated with a localized source of rising mantle, is present and centered beneath the high topography and large volcanoes of central Marie Byrd Land (LeMasurier 1998; LeMasurier and Rex 1991). An alternative hypothesis, which takes into account the broad distribution and contemporaneous development of volcanic centers throughout the southern Pacific Ocean, is that the magmatism arises from diffuse sources of melt from the underlying mantle (Finn et al. 2005).

The coexistence of active volcanoes with the active West Antarctic ice sheet creates an opportunity to address questions about the onset of continental glaciation and the fluctuations in volume of glacier ice during glacial cycles. Current indications are that thin glacial ice and alpine glaciers were present when alkalic volcanism began, 36 Ma (Wilch and McIntosh 2000). On volcano flanks and summits in central Marie Byrd Land, trim lines from glacial erosion record the waxing and waning of the West Antarctic ice sheet (Ackert 2000). In addition, the volcanic activity can be an aid to study of glacier ice for climate records. Layers of volcanic ash erupted from the high volcanoes, fell upon the ice sheet, and now form prominent dark layers within the glacier ice. The erupted materials can be dated with isotopic methods, so the ash layers now provide important time markers in the ice sheet that can be used to accurately determine ages for prior climate events (Dunbar et al. 2003).

Prior to 10,000 years ago, the West Antarctic ice sheet was at a maximum, but since then it has been in decline. Glacial geology research, including cosmogenic dating of glacial deposits upon granite bedrock in the Ford Ranges, indicates that since 10,400 ka, there has been continuous lowering of the ice sheet surface, with consequent exposure of the mountain peaks (Ackert 2000; Sugden et al. 2005). Overriding by a large regional ice sheet has given way to localized flow of ice within local glaciers, and melting of the ice sheet upon Marie Byrd Land continues today.

Geological Exploration

The first rock exposures discovered in Marie Byrd Land are those at Scott Nunatak and Prestrud Rock, on the coast of Edward VII Peninsula. The outcrops were charted in 1902 by the British National Antarctic Expedition. Samples of banded gneiss from these crags, collected in 1911 by Lt. Kristian Prestrud of the Eastern Sledge Party of Amundsen's Norwegian expedition, provided the first clues about the geology of Marie Byrd Land. Not until 1928 were nearby inland mountain ranges discovered during exploratory flights by Admiral Richard E. Byrd from the base at Little America. Byrd discovered the Rockefeller Mountains on Edward VII Peninsula and the Ford Ranges bordering the Saunders Coast. Byrd's second-in-command was Laurence M. Gould, a geologist, who was the first to examine the Byrd Coast Granite that makes up the Rockefeller Mountains (Gould 1931). During the geological sortie led by Gould in the year preceding Byrd's polar flight, one of the Byrd expedition's airplanes was lost in a severe wind storm. As a consequence of Admiral Byrd's air exploration of the area, the larger region was named Marie Byrd Land in honor of Byrd's wife.

The second Byrd Antarctic Expedition and the United States Antarctic Service Expedition ("Byrd III") of 1939–1941 investigated the geology and biology of the Ford Ranges in a systematic way. Topographic mapping was the objective the United States Navy's Operation Highjump, which acquired the high altitude aerial photography needed to develop the first accurate maps of the region. Notable scientists who participated in this and subsequent geology investigations in Marie Byrd Land, including traverses during the International Geophysical Year in 1957–1958, were Paul Siple and F. Alton Wade. Mt. Siple, a volcano located at 73°39′ S, 125°00′ W along the coast of central Marie Byrd Land, is named for Paul Siple. The US Antarctic Program Marie Byrd Land Survey of 1966–1967 made further progress in geological research. In the late 1980s, international (South Pacific Rim International Tectonics Expedition—SPRITE) and American (Ford Ranges Crustal Exploration—FORCE) geological research recommenced with new vigor and continues today. Current research focuses upon the transition from convergent to divergent tectonics along the margin of West Antarctica in Cretaceous time; character of the mantle and controls on volcanism; the climate record preserved in the ice of the West Antarctic Ice Sheet; and the processes and time frame for deglaciation.

CHRISTINE SIDDOWAY

See also **Beacon Supergroup; British National Antarctic *(Discovery)* Expedition (1901–1904); Byrd, Richard E.; Cosmic Rays; Glacial Geology; Glaciers and Ice Streams; Gondwana; History of Antarctic Science; Ice Ages; International Geophysical Year; Norwegian *(Fram)* Expedition (1910–1912); Plate Tectonics; Siple, Paul; United States *(Byrd)* Antarctic Expedition (1928–1930); United States Navy Developments Projects (1946–1948); Victoria Land, Geology of; Volcanoes; West Antarctic Rift System**

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MARINE BIOLOGY: HISTORY AND EVOLUTION

The present-day marine fauna of the Southern Ocean has been strongly influenced by plate tectonics, palaeoceanography, and the resulting global climate change. These historic processes had caused faunal extinctions of some animal groups, while others were able to survive or even thrive under the newly developed climatic conditions due to physiological adaptations.

The Mesozoic opening of the Southern Ocean and split-up of South America, Africa, and Antarctica is one of the largest gaps in knowledge on the evolution of this region. After the separation of Africa, the breakup between Australia and Antarctica started approximately 100 Ma ago and successively led to a beginning deepwater circulation between Australia and East Antarctica, which was not completely developed before Eocene or Oligocene (approx. 55–35 Ma). At that time, the complete development of the Antarctic Circumpolar Current (ACC) was interrupted only by the land bridge between South America and the Antarctic Peninsula. However, this large water mass already led to a successive climatic deterioration, cooling, and glaciation of Antarctica, especially in the east of the continent. Due to the opening of the Drake Passage approximately 32.5–34 Ma and the development of the Scotia Arc, the Circumpolar Current became effective and caused a further cooling of the Southern Ocean surface water. An extensive deepwater circulation formed between South America and the Antarctic Peninsula. These dramatic palaeoceanographic changes successively resulted in the generation of the psychrosphere, the cold world's deep-sea bottom water, which is linked to the surface water in polar areas. The cooling and glaciation of the continent is considered to be a key event for the evolution of many Antarctic marine species.

Today, the Southern Ocean is isolated by the Polar Front (PF, previously termed the Antarctic Convergence), which is the strongest jet of the ACC, which is characterized by high current velocities. Antarctic Bottom Water (AABW) is of special importance for benthic life in the deep sea both in Antarctica and in other oceans. It is generated at the Southern Ocean ice margins, is cold, is highly saline, and has been a factor in the isolation of the benthic faunas due to the Tertiary temperature changes. The Weddell Sea and the Ross Sea are the main sources of the AABW production. Because of its high density, this water mass sinks down the continental shelf and slope into the Southern Ocean abyssal zone, where it moves northwards, limited or diverted along ridges, troughs, and spreading zones towards other deep-sea basins. AABW generation depends on the sea-ice production, which in turn is dependent on atmospheric processes and temperatures. If AABW production was interrupted at any time in the past during interglacial periods, one barrier to colonisation would have been removed and benthic organisms from lower latitudes could have spread into the Antarctic. However, the interactions between sea-ice production and deep-water generation are complex, and the gradual changes of the recent glacial cycles are not yet completely understood. Until now, it was impossible to trace the influences of these historic changes on the evolution, development, zoogeography, and range extensions of pelagic or benthic organisms. A geography of the sea has recently been published for the pelagic realm. The fossil record of benthic organisms is very limited and the palaeontological record of deepwater taxa remains almost entirely unknown.

The cooling of the Southern Ocean approximates to an average temperature decrease of 0.003 °C per 1000 years, though evidence suggests this cooling has taken place unevenly in time, often in bursts over just a few million years. This has had a much less dramatic influence on the evolution and extinction of benthic species than on land organisms—the forests, land snails, amphibians, reptiles, and other groups have all gone. Many taxa also became extinct, especially in the Late Cretaceous, but some survivors underwent rapid radiations. The successive cooling, glaciation, and isolation of Antarctica and the subsequent extinction of faunal elements had a strong impact on the evolution and radiation (promoting rapid speciation) of many Antarctic marine species and resulted in the evolution of many key elements of the present-day benthic marine fauna. For example, krill, notothenioid fish, peracarid crustaceans, and pycnogonids radiated in the Southern Ocean like the marsupials in Australia, while decapod crustaceans (crabs and shrimps), cirripeds (barnacles), and teleostei (bony fish) are rare.

The near extinction of Antarctic reptant decapods in the Tertiary may be explained by physiological constraints related to haemolymph magnesium regulation capacities in the cold and by their reproductive strategies. The virtual disappearance of the Reptantia and the Teleostei caused the emergence of new adaptive zones previously occupied. These may have opened up opportunities for spectacular adaptive radiations, like for the brood-pouch-bearing Peracarida (Crustacea Malacostraca) and the notothenioid fishes. Such groups are considered to be "preadapted" to the climatic and biologic changes of the Southern Ocean. Notothenioidei thrive on the Antarctic continental shelf, probably because of the innovation of the glycopeptide antifreeze substances in their haemolymph.

Peracarida can be argued to have a variety of protective adaptations that help to reduce predation (such as by fish, which are especially speciose in benthopelagic or benthic environments). Larger species or species with a well-developed spine armature are not an easy prey for fishes (e.g., Epimediidae and Iphimediidae within the Amphipoda or Serolidae and Antarcturidae within the Isopoda). Some species use camouflage or mimesis (concealed mimicry) by having colourful pigment patterns on their cuticles. Spines can serve a similar function, blending their bearer into uneven backgrounds, such as algae, bryozoans, hydrozoans, or alcyonarians, as well as acting as protection against possible predators.

Radiations are the product of evolution in isolation over long periods of time and are connected with a high level (60%–90%) of endemism (organisms which have been reported in only that area) as is the case in sponges, bryozoans, and peracarid crustaceans, for example. However, these generalisations apply specifically to shelf faunas. It is currently unknown whether the often cited "typical" characteristics of the Antarctic fauna (e.g., the high level of endemism, gigantism, late maturity, decreased number of offspring, and high longevity, amongst others, also apply to Southern Ocean deep-sea fauna). Recent deep-sea expeditions (e.g., ANDEEP) have found endemism of deep-water isopod species to be ~85%, as high as on the shelf; however, this might be due to the still low sampling effort in the deep sea (of the Southern Ocean).

It was believed that many species had circumantarctic distributions, but there is growing molecular evidence that many of these actually comprise several cryptic species, presently undergoing speciation processes. For example, the isopod crustaceans *Ceratoserolis trilobitoides* (three cryptic species), *Glyptonotus antarcticus* (four species), and asellotes have all recently been described as having Southern Ocean species-complexes.

Many sessile suspension-feeding and other epifaunal groups have been particularly successful both ecologically (abundance) and evolutionary (species generation) on the Antarctic shelf in part due to the coarse-grained and poorly sorted, glacial-marine sediments. One might therefore wonder whether the Antarctic ice extension, followed by annual or cyclic retreats, has increased their success and the availability of hard substrates for them.

There are many hypotheses on the potential origin of the Southern Ocean fauna. It was first postulated that the ancestors of the Southern Ocean shelf species of isopod crustaceans evolved in the deep sea and migrated up onto the continental shelf (polar emergence). This would have been easier (than in other oceans) because of the absence of a thermocline. However, the contrary process, polar submergence of species from the shelf into the Southern Ocean deep sea has also been hypothesized. The ecological and evolutionary relationships of the faunas of southern South America and Antarctica were compared. This focussed on the possibility of species migration by island hopping via the Scotia Arc. If this was an important method, the Shackleton Fracture Zone in the Drake Passage might serve as a submarine bridge linking faunas of southern South America and the Antarctic Peninsula regions. The vicariance event of the fragmentation of the supercontinent Gondwana, into distant continents, has clearly led to disjunct distribution patterns within many faunal groups.

The present day Southern Ocean biodiversity is the result of different and simultaneously occurring biogeographic and evolutionary processes. These include the progressive retraction of taxa that used to have cosmopolitan distributions (established during the Jurassic and Cretaceous periods), disjunct distributions of genera or species due to continental drift vicariance, active migrations of taxa in and out of the Southern Ocean, and radiation events due to the emergence of new adaptive zones. As a proportion of the world, the Southern Ocean comprises ~8% by area, ~2% by coastline, and an intermediate level by shelf area. Whether the Southern Ocean marine ecosystem has a low or a high proportion of species relative to other regions depends on which of these figures is used for comparison. By ocean area, most higher organism groups are less rich than would be expected, a fact probably due to the low sampling effort below the continental shelf. By shelf area or coastline, many groups are richer than average across the world, especially the pycnogonids, polychaetes, ascidians, holothurians, amphipods, and bryozoans. Estimations of continental shelf biodiversity of the Antarctic are difficult because many geographic areas have not been sampled representatively, a huge number of new species await description, and the definition of shelf depth differs (it is unusually deep in Antarctica).

It is very probable that at no time during the Cenozoic did the Antarctic shelf ice sheet completely eradicate the Southern Ocean shelf fauna completely (there were probably refugia). However, during maximal ice extensions, ice masses would have extended to 1-km depth even north of the Antarctic Peninsula. Many Antarctic species investigated to date show wider bathymetric distributions compared with those in other seas, suggesting that many continental slope species found shelter in deeper waters off the shelf during glaciation events. The geological history of the breakup of Gondwana, the increasing isolation of Antarctica, and changes due to the Milankovitch (sun cycle) cyclicity have generated a cooling but fluctuating climate, and strongly determined the composition, distribution, and zoogeographic limits of organisms permanently. The subsequent changes in the ice-shelf extension probably led to speciation processes on the Antarctic continental shelf in some taxa, and to adaptive radiations. For this reason, some scientists refer to Antarctica as a diversity pump. It is unknown to what extent species have migrated up and down the Antarctic continental shelf and slope following ice extensions and retreats during glacial maxima and minima, but these processes are thought to have led to the high eurybathy that is characteristic for many Southern Ocean species today. Due to AABW production, the Weddell and Ross seas may have been an important source of taxa presently living in the Atlantic or Pacific deep oceans because the isothermal water masses surrounding the Antarctic continent provide an obvious conduit for the migration of shallow-water species into the Southern Ocean deep sea and further north. In this respect, the Antarctic shelf might indeed serve as a "biodiversity pump" conveying organisms or developmental stages from shallow to deeper sea areas of the Southern Ocean. Investigations on pressure tolerance, for example on the early larval stages of the sea urchin

Sterechinus neumayeri, have demonstrated theoretical ability to persist deeper than at 2-km depth.

Today, anthropogenic impacts, global climate change, natural selection, and evolution influence the biosphere. Southern Ocean shelf benthic communities have been reported to change due to increased physical disturbance, like iceberg scouring (which will be increased by global warming) or (on a local scale) sewage increase by humans. Climate models still have considerable levels of error associated with predictions of Southern Oceanic responses to global climate change, but increases in sea temperature, CO_2, glacial retreat, acidification of surface waters, UV-B, and precipitation all seem likely. Biological responses to these factors will affect, initially, the molecular level and determine population fitness and species interactions before it ultimately might affect biogeochemical cycling. Moreover, physical feedback of global climate change will regulate sea ice and primary production, winds, and thermohaline ocean circulation, all of which have further biological impacts and—like in the Late Cretaceous and Cenozoic—might force organisms to survive at greater depths in the Southern Ocean again.

ANGELIKA BRANDT

See also **ANDEEP Programme; Antarctic Bottom Water; Biodiversity, Marine; Benthic Communities in the Southern Ocean; Biological Invasions; Circumpolar Current, Antarctic; Climate Change; Deep Sea; Drake Passage, Opening of; Fish: Overview; Gondwana; Plate Tectonics; Polar Front; Ross Sea, Oceanography of; Weddell Sea, Oceanography of; Zooplankton and Krill**

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MARINE DEBRIS

In the last few thousand years, humans have increasingly used the sea and launched floating material into it. About four decades ago, a new, most numerous and durable source of material started entering the oceans—plastics. Within this time the world's shores have revealed the changes in material afloat as plastic artefacts have rapidly accumulated on high-water marks. In Antarctica, a continent that has not had forests for a considerable period nor surface-dwelling (floating) animals, this has been particularly dramatic. A few years ago the first recorded visit took place to one of the remote South Sandwich Islands, but plastics had already covered a stretch of its shoreline. Natural flotsam does also occur, however. Tree trunks can occasionally wash up on Antarctic (mainly sub-Antarctic island) shores as do other biological propagules such as seeds. Unlike in other oceans, human (and other) debris is limited in its range; items rarely wash up on shores south of $\sim$63° S. In the Southern Ocean, the source of much marine debris are fisheries vessels, for example at Macquarie Island, Bird Island (South Georgia), and Livingston Island. However, a study of the annual debris accumulation patterns at Signy Island found little correspondence with the local krill fishery. At these localities and a few others (mostly sub-Antarctic and maritime Antarctic island sites), accumulation rates, and the nature and sources of debris are recorded at the request of CCAMLR. Where accumulation rates have been recorded (around Antarctica this ranges from 0.01 to 1 item/km/yr), there is mixed evidence of whether rates are still increasing. Dumping of plastics is now banned according to MARPOL Annex V, and in 1993, CCAMLR began applying conservation measure 63/XII phasing out plastic banding. Floating plastic debris is still relatively rare south of about 60° S.

There are a number of changes to the sea-surface and shore environments associated with man-made marine debris, such as plastics. Aside from aesthetics, it can poison, starve, and choke wildlife that swallow or become entangled in it, such as seabirds and seals. Plastic packaging bands can be regularly seen entangling and cutting into fur seals at the sites where there are large colonies. Below the surface, nylon fishing nets can "ghost fish" for considerable periods until they sink. A quite different issue is alterations to transport opportunities for organisms. In warmer waters, hitchhikers from microbes to iguanas travel on marine debris to colonise new coasts. Marine debris is now known to be able to cross the Polar Front, both northwards and southwards, enabling any attached organisms to reach new environments. The freezing surface of Southern Ocean waters were thought to be a barrier to floating colonists, but in 2003 several groups of organisms (namely polychaetes worms, bryozoans, hydroids, sponges and a mollusc) were found on a single plastic piece and some were more than a year old. Colonists can be so numerous that they can be important food sources. Birds have regularly been seen crowding to feed on stalked (pedunculate) barnacles attached to buoys and floating plastics washing ashore at Macquarie Island.

David K. A. Barnes

See also **Antarctic Fur Seal; Biological Invasions; Conservation; Macquarie Island; Polar Front; South Georgia; South Sandwich Islands; South Shetland Islands; South Orkney Islands; Southern Ocean**

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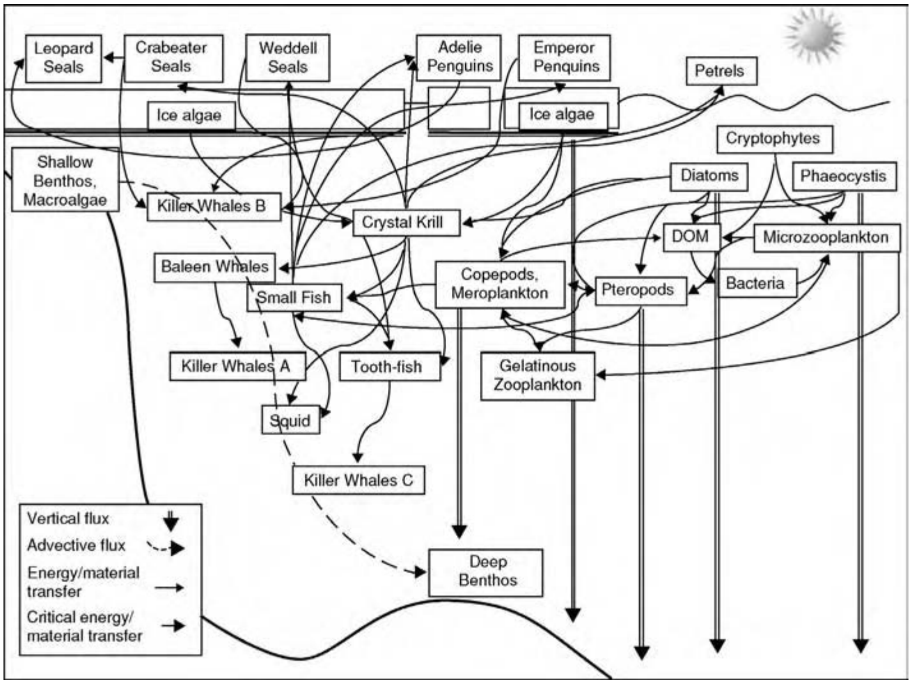
MARINE TROPHIC LEVEL INTERACTIONS

Ecological interactions among different trophic levels are critical connections that link the food web with the environment and material cycles. While the nature of these interactions is not different in waters of the Southern Ocean, there are species that exist in the Antarctic that are unusual in their importance to the food web. These species can occur at various trophic levels (the level within the food web at which an organism feeds), and their interactions with the environment and other organisms is critical in understanding their role in food webs. Food webs vary within the regions of the Antarctic, and the interactions between trophic levels is often poorly quantified.

At the first trophic level (that of the autotrophs), one critical interaction is the interaction of phytoplankton with the oceanic environment. This interaction controls the growth, abundance, and distribution of taxa (or of functional groups, related species that apparently occupy similar ecological niches). An example of this connection is that of the environment with an alga called *Phaeocystis antarctica*. This species apparently grows in waters with relatively deep mixed layers (and therefore relatively low irradiance levels) and elevated iron concentrations. This species is important because it has an unusual chemical composition, releases large amounts of volatile sulfur compounds (which enter the atmosphere and modify local climate), and in some locations is a poor food source for herbivores. Another important environment-functional group example is that of diatoms, which grow in high irradiances and slightly lower iron concentrations. Hence, in at least some locations in the Antarctic, there is a separation in time and space of these two functional groups.

Ice algae grow on and within pack ice throughout the Antarctic, and those groups have a strong linkage with their unique environment. For example, when pack ice begins to melt during the summer, ice algae (being highly colored) absorb solar energy and can enhance basal melt rates (and hence rates of algal release to the ocean). During melting, brine is released and creates a complex, three-dimensional matrix that provides refugia from predation for some organisms. Similarly, as frazil ice forms during austral autumn in the upper 10 m, it rises to the surface and many algal particles "stick" to the crystals, only to be incorporated into the pack ice.

Another important ecological interaction is that between the environment and Antarctic krill *(Euphausia superba)*, often called a keystone species of the Antarctic. Because of their size, krill (especially subadults) move with the water masses, and this large-scale



Representation of the food web of the continental shelf of the Ross Sea. (From Smith et al., in press.)

movement is a major factor in controlling their distributions. Krill also have a complex life cycle that includes laying of eggs at the surface, the obligatory sinking to depth (500–1000 m) to complete the larval development, and then their return to the surface by active swimming. If the eggs sink to the sediments, they are quickly eaten by benthic organisms, which means that krill development always occurs in waters off the continental shelf. If they sink to depths greater than 1000 m, their survival is reduced because they do not have internal food stores great enough to support metabolism prior to migration to the surface and subsequent feeding. Their development and vertical migration rates are also temperature dependent, and successful development is enhanced by passing through waters (>1°C) that are slightly warmer than those at the surface. Krill also require high concentrations of their phytoplankton food once they return to the surface, and utilize the complex circulation patterns to be advected to high-food regions to begin feeding.

Adult krill also form accumulations called swarms (densities up to 250 g m^{-3} and 20 m thick). These elevated densities are important in that they provide a concentrated food source for higher trophic levels (such as whales, seabirds, penguins, and seals), and also may serve as a protection against losses in a manner similar to fish schooling. The generation of swarms is due to the interaction between the vertical migration patterns of krill and the small-scale movement of near-surface water. Swarms will then be moved by the large-scale patterns of circulation over long distances as well. Other environmental factors such as food concentrations and irradiance also influence swarming behavior.

Feeding by a variety of species on krill demonstrates another critical feature of species interactions in the Southern Ocean. Many top predators, such as seals, seabirds, and penguins, nest on land and forage for food at sea. Thus they are spatially restricted to regions close to their colonies and nests. Yet there is specific foraging behavior of each group that separates them and reduces competition while searching for food. Such differences can include the depth of dives, the duration of dives, and the distance from nests. All of these also vary based on the amount of prey available as well; furthermore, prey availability is dependent on the season, their food, and other factors.

Perhaps the most important species interactions in the Southern Ocean are those involving man. In the past 100 years, whaling in the Antarctic dramatically reduced the populations of *all* species hunted: humpback, blue, fin, sei, and minke whales. Other species, such as fur seals, also were overexploited, as human technology allowed for rapid decimation of stocks. A number of fish stocks have been overharvested as well, and these fish species have slow growth rates; these populations have not returned to anything approaching preharvest levels. Finally, there has been and continues to be great interest in harvesting krill. Many problems exist with regard to the exploitation of this species, but if the economic need to catch krill increases, it is likely that the krill stocks could also be severely affected. Given the preeminent role of the species in Antarctic food webs, use of this species should be done with extreme caution, and the role of CCAMLR in ensuring trophic level sustainability will be crucial.

Trophic-level interactions occur between trophic levels, within trophic levels, between similar species, and within the same species. These linkages vary in space and time, and respond to other changes within the entire food web. They ultimately control the material and energy flows within the ecosystem; understanding those interactions provide a basis for understanding all food webs of the Antarctic marine ecosystems.

WALKER O. SMITH, JR.

See also **Algae; Antarctic Fur Seal; Benthic Communities in the Southern Ocean; Blue Whale; Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Fin Whale; Fish: Overview; Food Web, Marine; Humpback Whale; Larvae; Minke Whale (Antarctic Minke Whale); Pack Ice and Fast Ice; Penguins: Overview; Phytoplankton; Sea Ice: Types and Formation; Seals: Overview; Sei Whale; Whales: Overview; Whaling, History of; Zooplankton and Krill**

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MARKHAM, CLEMENTS

Sir Clements Markham never went to the Antarctic. He nevertheless was a key figure in the history of the Antarctic because, as president of the Royal Geographical Society, he was the driving force that set in motion the renewal of British Antarctic exploration towards the end of the nineteenth century.

Born on July 20, 1830, at Stillingfleet in Yorkshire, the son of a clergyman, he entered the Royal Navy as a cadet in 1844, serving first on the Pacific Station, learning French and Spanish, as well as navigation and seamanship. It was from the decks of the wooden sailing warship HMS *Collingwood* in 1845 that he first set eyes on Peru, which was to become the first love of his life. (The polar regions were later to become the second.) He was allowed ashore with other midshipmen, and his fascination with the people and country led him to return to Peru in 1852–1853—soon after leaving the navy—to investigate its antiquities and to travel widely. He had learnt Quechua, the language of its people, during a winter in the Arctic, and he visited a number of priests in remote villages to learn about the history and literature of Peru. He returned again in 1859–1860 to procure young plants and seeds of the cinchona tree on the eastern slopes of the Andes. At his initiative, the newly established India Office had sent him and two others (one being Richard Spruce) to transplant these in India for the production of quinine, which would benefit both the Indian people and British officials and armed forces.

In 1850–1851, while still in the navy, he had played a small part in the search of Sir John Franklin, whose ships HMS *Erebus* and HMS *Terror* had disappeared in the Arctic during the last of the Admiralty expeditions to find the Northwest Passage. Markham's ship was *Assistance,* under Captain Erasmus Ommanney, part of a squadron commanded by Captain Horatio Austin. The first traces of Franklin were found on Beechey Island. Markham was a foremost contributor to the ship's winter newspaper, the *Aurora Borealis,* which was published on the expedition's return as *Arctic miscellanies*.

Throughout his life, Markham's literary output was considerable, beginning with translations from the Spanish of narratives relating to the conquest of the Incas and the history of Peru. These volumes were largely published by the Hakluyt Society, of which he became honorary secretary for 28 years, and later president for nearly 20. He wrote a short account of the Franklin search expedition, in which he had taken part, under the title *Franklin's Footsteps*.

Together with Sherard Osborne, who had also taken part in the Franklin search, Markham ran a campaign to renew Arctic exploration. This resulted in the British Arctic Expedition (1875–1876), commanded by Sir George Strong Nares in HMS *Alert* and HMS *Discovery*. Markham sailed as far as West Greenland in *Alert,* overstaying his allowance of leave and consequently having to resign his post as geographer at the India Office, during which period he had rescued from oblivion many historic records. He appears to have earned his living after that from his literary works, of which he published a prolific number.

He was installed as president of the Royal Geographical Society in 1893 and was knighted in 1896 for his "great services to geographical science." With the eminent oceanographer Sir John Murray, of *Challenger* fame, he opened the campaign to renew the exploration of the Antarctic regions. These had last been visited in the 1840s by three national expeditions. The government would not commit itself to financing another official undertaking, but did make a considerable grant towards the cost of what became the British National Antarctic Expedition of 1901–1904. A number of naval officers and ratings were allowed to join, among them the leader, Robert Falcon Scott. Markham had first noticed Scott as the youthful winner of a cutter race. He became Markham's protégé, but also received the recommendation of one of his old captains in the navy.

The Antarctic campaign broadened in its scope at the International Geographical Congress of 1895, held in London with Markham as its president. It passed the motion that the exploration of the Antarctic regions "was the greatest piece of geographical exploration still to be undertaken." Learned societies throughout the world should urge that the task should be begun before the end of the nineteenth century. It took years for Markham to amass funds enough to build *Discovery* at Dundee and for her to depart in August 1901 on a programme of Antarctic geographical exploration and scientific observations. He had brought in the Royal Society to cooperate in the organization of the expedition, but found relations with what he called "wild professors on the warpath" not at all easy. Their differences mainly concerned the geographical and scientific work on the expedition. In this, Markham triumphed: the exploration of the unknown interior of the continent was to be the main object (rather than what he called "mud larking": oceanography), and Captain Scott was to take charge of the scientific programme. The Royal Geographical Society became owner of *Discovery,* with Markham as her "Managing Owner." He chose the relief ship *Morning* in Norway and greatly appreciated the efforts of her master, Captain William Colbeck, during two Antarctic voyages, making a special presentation to him at the Royal Albert Hall on the occasion of Scott's lecture in November 1904.

Markham stood down as president of the RGS in 1905. He played little part in the organization of Scott's *Terra Nova* expedition, 1910–1913, but was greatly saddened by the deaths of the Polar Party in the Antarctic. He died on January 30, 1916, following an accident in which he set light to his bedding. A fine portrait in oils of him in old age, featuring the cinchona plant and the silver model of an explorer with his sledge, was painted by George Henry, ARA. It hangs, fittingly, at the Royal Geographical Society.

ANN SAVOURS

See also **British Antarctic *(Terra Nova)* Expedition (1910–1913); British National Antarctic *(Discovery)* Expedition (1901–1904); *Challenger* Expedition (1872–1876); Royal Geographical Society and Antarctic Exploration; Scott, Robert Falcon**

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MARR, JAMES

James William Slesser Marr was born at Cushnie, Auchterless, Aberdeenshire, on December 9, 1902, and educated at Aberdeen Grammar School and the University of Aberdeen. At age 18, while at university, he was chosen from many volunteer Boy Scouts to accompany the Shackleton-Rowett Antarctic Expedition (1921–1922) aboard *Quest* to explore the coasts of the Weddell Sea and a number of little-known sub-Antarctic islands. From that time he acquired the nickname "Scout" Marr, which he resented. He was a young man of very powerful build, who quickly responded to Ernest Shackleton's great leadership and was held in high regard by all hands for his performance of duties. He was in the ship at Grytviken, South Georgia, in 1921, when Sir Ernest died.

On his return from the Antarctic, Marr graduated from the University of Aberdeen with an MA in classics in 1924, and then took his BSc in zoology in 1925. In that summer he took part in the British Arctic expedition in the ship *Island* under the leadership of Grettir Algarsson and Frank Worsley, which made a modest contribution to exploration and research, and circumnavigated Spitsbergen. Marr lost no chance to put out tow-net and dredge, and returned to the Marine Laboratory in Aberdeen to spend a year as a Carnegie scholar to work up his marine collections.

In 1927 Marr was appointed to the scientific staff of the Discovery Investigations. In this service he took part as marine biologist in three expeditions to the Antarctic—in *William Scoresby,* 1928–1929, and in *Discovery II,* 1931–1933 and 1935–1937. In 1929–1931 he was seconded to the British Australian New Zealand Antarctic Research Expedition under the leadership of Sir Douglas Mawson in *Discovery*. For all this service he was awarded the Polar Medal in Bronze, with clasps Antarctic 1929–1930 and 1928–1937. He later published his marine biological work in his definitive report, *Antarctic Krill.*

In 1939–1940 Marr again voyaged south as an inspector in the whaling factory ship *Terje Viken,* while seconded to the Department of Scientific and Industrial Research to investigate the possible use of canned and frozen whale meat to augment British wartime food stocks.

On his return from the Antarctic, Marr joined the Royal Navy as a lieutenant commander, RNVR, and saw service in Scotland, Iceland, South Africa, and Ceylon, until 1943, when he was recalled home to organize and lead the secret Operation Tabarin, designed to resume British activities in the Falkland Islands Dependencies (now British Antarctic Territory), and to safeguard British interests and sovereignty in that region. It thus fell to Marr to bridge the gap between the prewar British private expeditions and the new era of government-supported exploration and research.

Operation Tabarin was mounted in little more than 4 weeks, and involved huge problems in finding equipment, supplies, and shipping, so that it is astonishing that the two initial bases at Deception Island (South Shetland Islands) and at Port Lockroy (Anvers Island) were established so expeditiously. Marr himself was exhausted by this major effort, and was invalided home in 1945 at the end of the first winter at Port Lockroy, turning over to his second-in-command. For his service he was awarded the Polar Medal in Silver, being one of only eighteen men to receive both Bronze (abolished after 1942) and Silver Polar Medals. He is commemorated in two Antarctic place-names.

After the war Marr was able to resume his work as principal scientific officer at the National Institute of Oceanographic Research, an appointment he held until his death. He died on April 29, 1965, survived by his wife Dorothea Helene (Plutte) and five of their six children.

GEOFFREY HATTERSLEY-SMITH

See also **British Antarctic Survey; British, Australian, New Zealand Antarctic Research Expedition (BANZARE) (1929–1931); Discovery Investigations (1925–1951); Mawson, Douglas; Shackleton, Ernest; Shackleton-Rowett Antarctic Expedition (1921–1922); South Shetland Islands; Worsley, Frank; Zooplankton and Krill**

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MAWSON, DOUGLAS

Douglas Mawson, Australia's greatest Antarctic explorer, was born May 5, 1882, near Bradford, Yorkshire, England, and immigrated to Australia in mid-1884 with his parents and elder brother. He was educated at the University of Sydney (BEng, 1902, focus on geology and mineralogy; BSc, 1905). His mentor was Professor (later Sir) T. W. Edgeworth David, a renowned geologist with inordinate political pull. During 1903, Mawson undertook a geological survey of the New Hebrides. In 1905, the University of Adelaide appointed him lecturer in mineralogy and petrology, and he began field studies of the geology (much of it glacial) of the region from the Flinders Ranges to Broken Hill.

When Ernest Shackleton visited Adelaide en route to Antarctica in 1907, Mawson asked to join his British Antarctic Expedition, to which David had already been accepted. Mawson's interest in glacial geology was a prime motivator, together with his adventurous spirit, and no doubt he thought that doing some Antarctic geology would further his career. He initially only wanted to travel south on the expedition ship *Nimrod* and then return when the land party was left behind. Shackleton, however, appointed him physicist for the duration of the expedition, and Mawson gained permission from the University to remain for the length of the expedition. Mawson was one of the party of six that first scaled Mount Erebus, the active volcano on Ross Island. The next summer, he was one of three (under David's leadership) who first reached the area of the South Magnetic Pole (summer, 1908–1909). Without the aid of dogs, Mawson, David, and Alistair Mackay dragged their sledges for 1260 miles (2030 km) on this trek. The route they chose for the return proved treacherous, food ran low, their survival was a near thing, and Mawson took over command from an exhausted David. They were only just rescued by *Nimrod,* when the first officer, John King Davis, convinced the captain to return to an area they had already searched, prior to leaving the party to their fate.

In Australia, Mawson and David were received as heroes, and Mawson began to conceive plans for an Antarctic expedition of his own. These took shape from February 1910. On a visit to England—having turned down an offer to join Robert Falcon Scott's expedition—Mawson won Shackleton's support, but not the large-scale funding Shackleton's connections had seemed to promise. While continuing his position at the University of Adelaide, Mawson found his own funding sources and proceeded with the planning of what became his Australasian Antarctic Expedition (AAE, 1911–1914).

The AAE received some government support but was largely a private affair. Conceived under the aegis of the Australasian Association for the Advancement of Science, from the outset it put science first. J. Gordon Hayes, writing of its scale and achievements, called it "the greatest and most consummate expedition that ever sailed for Antarctica" (Hayes 1928: 210). It was on a scale never before conceived for Antarctica: a serious scientific investigation with three continental bases stretched along a 2000 mile (3200 km) arc of coast, which would also be explored geographically, with each base sending teams east and west (hopefully to link up), and one party going south as well. In the event, Mawson was forced to reduce the continental bases from three to two.

The site for the Main Base was Cape Denison in Commonwealth Bay, Adélie Land. A second continental base was set up under Frank Wild some 1500 miles (2400 km) to the west, on the Shackleton Ice Shelf. Between the bases, seven major sledging trips were sent over entirely unknown territory, all in the face of extremely difficult weather. The Main Base, in particular, earned a reputation as the windiest place in the Antarctic.

The event that cemented Mawson's heroic reputation was his amazing return from the death of his two sledging companions. On November 10, 1912, he set out with Dr. Xavier Mertz, Lieutenant B. E. G., Ninnis, and two dog teams heading southeast, then east. A month out, 311 miles (500 km) from Main Base, Ninnis was killed when he fell into a crevasse, taking with him their best dogs and most of their food and equipment. With few supplies left, there followed a desperate return journey, on which Mawson and Mertz turned to their dogs for food. More than half way back, Mertz sickened and died; Mawson, also in terribly ill condition, continued alone. Finally, on February 8, Mawson reached Main Base, to find that the expedition ship, *Aurora,* had picked up most of the men and, after waiting weeks for his return, had sailed away only hours before to collect the members of the Western Base. With a small party that had remained behind to search for him, Mawson had to wait another year before he could return home. The next summer the party was relieved, and Mawson and the others arrived back in Australia in late February 1914. He was knighted later that year in London, and the following year his account of the expedition, *The Home of the Blizzard,* was published in two volumes. Mawson spent many years overseeing the publication of the scientific results of the AAE.

Mawson married his fiancé, Francesca Adriana ("Paquita") Delprat, soon after his return to Australia. After spending much of the following year travelling and lecturing in an attempt to repay the debts of the expedition, he served in the First World War, much of it with the Ministry of Munitions in England. He then returned to the Department of Geology at the University of Adelaide, where he was made professor of geology and mineralogy in 1921.

Mawson's British, Australian, New Zealand Antarctic Research Expeditions (BANZARE) of 1929–1931 were overtly imperial ship-based expeditions that also employed a seaplane. Among the discoveries were extensive regions between Adélie Land and Enderby Land, including Banzare Land, Princess Elizabeth Land, and Mac.Robertson Land (all named by Mawson). New features were charted, known features charted more accurately, new mountain ranges observed, and landings made on the mainland (at Scullin Monolith and Cape Bruce). Australia's Antarctic claims were direct results of Mawson's expeditions and his own efforts at science and exploration.

Mawson had a long career at the University of Adelaide, and his fieldwork in South Australia was extensive and important. He was a founding Fellow of the Australian Academy of Science, and played a significant role in the early planning of the Australian National Antarctic Research Expeditions (ANARE). Throughout his life he remained a figure of prominence and influence in scientific and Antarctic circles throughout the world. He died in Adelaide on October 14, 1958, and was given a Commonwealth state funeral.

PHILIP AYRES

See also **ANARE/Australian Antarctic Division; Australasian Antarctic Expedition (1911–1914); British Antarctic *(Nimrod)* Expedition (1907–1909); British, Australian, New Zealand Antarctic Research Expedition (BANZARE) (1929–1931); David, T. W. Edgeworth; Davis, John King; Shackleton, Ernest; Wild, Frank**

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McMURDO STATION

McMurdo Station is the scientific and operational hub of the United States Antarctic Program. Its location on the ice-free southern tip of Ross Island at the southwestern corner of the Ross Sea is geographically unique in ways that make it valuable for supporting scientific research:

- The high latitude of 77°51′ S—838 miles from the South Pole—has made it the compelling location for more than 100 years as a launching point for expeditions that have explored and studied much of the Antarctic.
- Its protected natural seaport—Winter Quarters Bay—accommodates deep draft cargo ships and tankers, enabling economical seaborne delivery of 95% of all fuel and cargo used by the United States Antarctic Program in continental Antarctica.
- Winter Quarters Bay is the world's southernmost port.
- Sea ice on adjacent McMurdo Sound and glacial ice of the nearby Ross Ice Shelf have proved practical for landing large transport airplanes with normal, wheeled landing gear arriving from overseas (Christchurch, New Zealand, 2350 miles to the north).
- The station site has several square miles of gently sloping, ice-free solid ground on which safe and efficient buildings have been constructed using techniques comparable to ordinary methods of the lower latitudes.
- The site is not and was not inhabited by wildlife colonies; ecological impact is minimal.

The locale is historic, having been discovered in 1839–1840 and used as the coastal base of expeditions toward the South Pole in the first decade of the twentieth century, most notably Robert Falcon Scott's British National Antarctic Expedition, which established the first hut there. The US Navy's Operation Highjump made reconnaissance flights over the Transantarctic Mountains from McMurdo Sound in 1946–1947. On 29 January 1948 during Operation Windmill, the US Navy icebreakers *Edisto* and *Burton Island* put parties ashore and studied the nearby ice shelf.

On 18 December 1955 the navy's icebreaker, *Glacier,* entered McMurdo Sound, beginning construction of McMurdo Station. The first function was as the logistics base from which to construct and support a research facility at the geographic South Pole for the 1957–1958 International Geophysical Year. After the IGY, McMurdo grew to be an operational and science center that now is the largest human settlement in Antarctica.

McMurdo's logistics centers on airlift within Antarctica and both airlift and sealift between it and the United States. This capability enables support not only of the year-round Amundsen-Scott South Pole Station, but also of the dozens of research camps established throughout the continent every summer and a complete program of waste management functions.

While McMurdo Station is occupied year-round, it has a distinctive annual cycle of population and activity that rises and falls with the Sun. In mid-August, McMurdo's Pegasus runway, on prepared glacial ice, receives several round-trip flights from New Zealand, ending the winter crew's isolation and nearly doubling McMurdo's population from 241 (in 2005) to about 400. From the beginning of October to the end of February, about three flights a week arrive from New Zealand on the Pegasus runway or on a temporary runway built each summer on the annual sea ice of McMurdo Sound. US Air Force C-17s make most of these intercontinental flights.

The McMurdo population rises quickly in October to about 1100, mostly Americans but including substantial numbers of scientists and support personnel from other Antarctic Treaty nations cooperating with their US counterparts. The South Pole population rises from eighty-six (in 2005) in winter to a summer peak exceeding 220, and the population of field camps rises from 0 in winter to a peak of about 136 in summer. Population drops quickly in late February to the winter level, at which it remains until August.

Substantial collaboration in air transport between Christchurch and McMurdo takes place with other Antarctic Treaty nations—particularly New Zealand, whose year-round Scott Base is 2 miles from McMurdo, and Italy, whose Terra Nova Bay station is 200 miles away.

McMurdo is the hub for US air transportation throughout the continent. In addition to the two runways described above, a skiway named Williams Field is near McMurdo on the Ross Ice Shelf; ski-equipped airplanes can use it at any time of the year. The airplane fleet for operations within Antarctica typically consists of six ski-equipped C-130s (designated LC-130s) and two or three ski-equipped Twin Otters. Helicopters, typically two AS-350B and two Bell 212 helicopters, operate from a heliport within McMurdo Station.

Satellite ground equipment at nearby Black Island, connected by microwave to McMurdo, provides the station with full-time telephone, e-mail, and Internet service as well as real-time access to some US radio and television broadcast channels.

Diesel engines generate electricity, and their "waste" heat warms buildings and helps desalinate seawater (using reverse osmosis) to make the station's water supply. Insulated and heat-taped pipes carry water and sewage throughout the station; sewage is treated before its remnant clean water is discharged into the sea.

The station's ninety or so buildings include a large multidiscipline science laboratory with aquaria, facilities for equipping field science parties, shops, a library, storage, and dormitories and dining areas.

Ross Island is ideally situated for Antarctic science. It is within helicopter range of southern Victoria Land, whose Transantarctic Mountains and McMurdo Dry Valleys have geological and biological complexities still not completely understood. It is not far from Weddell seal, Adélie penguin, and other wildlife colonies, whose documented behaviors and population changes offer insights into simple and remote ecosystems that manage to flourish in some of the planet's most extreme environments. It is within practical airplane range of the West Antarctic Ice Sheet, whose response to and influence on world climate and sea level are being studied intensively.

The functions of McMurdo Station are critical to most of the US Antarctic Program. The station in 2005 was expected to operate into the foreseeable future. However, an unprecedented array of large icebergs, stalled north of the station in the early years of the twenty-first century, complicated ship and icebreaker transit to the station and caused the National Science Foundation to consider alternatives to the McMurdo location.

GUY G. GUTHRIDGE

See also **Amundsen-Scott Station; Archaeology, Historic; Aviation, History of; Base Technology: Architecture and Design; Base Technology: Building Services; British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); British National Antarctic *(Discovery)* Expedition (1901–1904); Dry Valleys; International Geophysical Year; Office of Polar Programs, National Science Foundation, USA; Ross Ice Shelf; Ross Island; Scott, Robert Falcon; United States: Antarctic Program; United States Navy Developments Projects (1946–1948)**

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McMURDO VOLCANIC GROUP

The McMurdo Volcanic Group is the formal stratigraphic name used by geologists to describe Cenozoic volcanic rocks erupted in the western Ross Sea and Central Transantarctic Mountain areas of Antarctica. The original definition included volcanic rocks at the Balleny Islands, but these are now excluded as they were erupted in an oceanic environment and not on continental crust, as was the bulk of the McMurdo volcanics. The Cenozoic is the period of geologic time ranging from 65.5 million years to the present day.

Some investigators refer to the McMurdo Volcanic Group as the McMurdo Igneous Complex. Geologic mapping of rocks in north Victoria Land has identified small early Cenozoic bodies of alkalic igneous rocks. They are likely to represent the subsurface remains of a volcanoes magma chamber. These rocks are known as the Meander Intrusives and represent the oldest McMurdo Volcanic Group rocks. The McMurdo Volcanic Group rocks are all within the continental part of the Antarctic tectonic plate. They lie within and adjacent to the Victoria Land basin, in the western Ross Sea, which started forming about 100 Ma during the final stages of the breakup of the Gondwana supercontinent. The continental crust still continues to be thinned by rifting. Lavas and eruptive products of the McMurdo volcanics typically have high contents of sodium and potassium giving them an alkalic compositions. Alkalic magma compositions are widespread in continental rifts.

The McMurdo Volcanic Group has been subdivided into the Hallett, Melbourne, and Erebus volcanic provinces. The Hallett volcanic province consists of a 260-km-long chain consisting of four major elongate shield volcano complexes (Adare, Hallett, and Daniell peninsulas and Coulman Island). They lie along the margin of the Transantarctic Mountains. Initial interpretations suggest the volcanoes were erupted in a subglacial environment when the ice sheets were larger. More recent work believes the volcanoes were erupted mainly under subaerial conditions. The Melbourne volcanic province consists of volcanic vents forming an arcuate band extending from the active Mount Melbourne on the coast to the large volcanic centers of Mt. Overlord, The Pleiades, and Malta Plateau lying on the Transantarctic Mountains. Small basaltic vents are widely distributed in the Melbourne province. The Erebus volcanic province is better studied and includes the numerous volcanic centers in McMurdo Sound, Beaufort, and Franklin Islands and marine volcanic centers in the southwest Ross Sea. Magnetic anomalies detected during geophysical surveys over the western Ross Sea are interpreted as small volcanic vents and included in the Erebus province. Ross Island is a coalescence of three major volcanoes (Mounts Bird, Terror, and Erebus) and is younger than 5 million years. In southern McMurdo Sound the Discovery subprovince is mostly older than 5 million years and includes the major volcanic complexes of Mounts Discovery and Morning and the linear fissure controlled vents on Minna Bluff and Brown Peninsula. Numerous other small basaltic centers are scattered along the foothills of the Royal Society Range and in the Dry Valley.

PHILIP R. KYLE

See also **Mount Erebus; Plate Tectonics; Ross Island; Transantarctic Mountains, Geology of; Volcanoes**

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MEGA-DUNES

Mega-dunes were first described by Swithinbank (1988), who termed these features based on their likeness to transverse sand mega-dunes. These features are extensive on the remotest part of the East Antarctic plateau and occupy more than 500,000 square kilometers. The climatic conditions of mega-dune areas are characterized by low temperature, extremely small snow accumulation, and very uniform wind direction and speed. They are oriented perpendicular to the regional katabatic wind direction, amplitudes are small (about 3–4 m), wavelengths range from 2 to over 4 km, and mega-dune crests are nearly parallel and 10 to 100 km in length. Leeward faces are characterized by a flat smooth layer of cemented thin films of ice (wind crust), which cover extremely large snow crystals (up to a centimeter). Windward faces are covered by large rough surface morphology (sastrugi) up to 1.5 meters in height.

Mega-dunes rise only a few meters above the general surface level and are imperceptible to the surface traveller. The regular pattern of sastrugi and wind crust allows us to survey the mega-dunes by satellite observations. The study of mega-dune genesis indicates that the change of slope along the prevalent wind direction (from less of 0.5 m km^{-1} to 1–1.5 m km^{-1}) plays a crucial role since it generates a wave in the katabatic wind, of weak amplitude (3–4 m). Mega-dunes are formed by snow accumulation variability due to katabatic wind waves. This variability ranges between 25% (leeward faces) to 120% (windward faces) of the accumulation in adjacent non-mega-dune areas. Mega-dune internal structure suggests the sedimentary morphology of the windward face (sastrugi) migrates upstream with time, burying the wind crust of the leeward face. The velocity of migration is some meters per year but the ice is flowing downhill at about the same rate. So a century-long "movie" of satellite images would show the mega-dunes moving sideways across the face of the ice sheet. The reconstruction of past climates based on ice cores drilled in areas with high snow accumulation spatial variability is distorted. In mega-dunes areas the distortion of recordings is characterized by a snow accumulation periodicity of about 1500 years. The length of periodical variations due to mega-dunes is correlated with ice velocity and snow accumulation, and can therefore vary in space and time.

MASSIMO FREZZOTTI

See also **Antarctic Ice Sheet: Definitions and Description; CryoSat; Firn Compaction; Glaciers and Ice Streams; Ice–Atmosphere Interaction and Near Surface Processes; Ice Sheet Mass Balance; ICESat; Snow Post-Depositional Processes; Surface Features**

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METEORITES

Very few extraterrestrial objects known as meteorites are recovered each year in the populated world. Only about 2000 stone or iron meteorites were known in 1970, either as observed falls or as later recognized finds. This number changed dramatically after Japanese glaciologists found nine meteorites of different types on a blue ice field near the Yamato Mountains, Dronning Maud Land. This high density of meteorites suggested the action of a concentration mechanism in the Antarctic and initiated systematic meteorite searches in the Antarctic, mostly along the Transantarctic Mountains and in Dronning Maud Land. By 2004, more than 30,000 meteorite fragments had been recovered, possibly representing as many as 6000–10,000 individual falls.

There are several reasons for high meteorite concentrations on some ice fields. (1) In visual surveys the recognition of meteorites is easy on blue ice fields. This is demonstrated by the mean mass of Antarctic finds, which is about 10 g, much smaller than the 1 kg or so of non-Antarctic meteorites. (2) Concentration mechanisms work by glacial movements, and ice flow is blocked or slowed by bedrock barriers. Where mountains or subsurface obstructions block the glacial flow and loss of ice is created by sublimation, meteorites fallen on the Antarctic continent are exhumed and stored on the ice surface together with direct meteorite falls. Small meteorites (<100 g) can be moved by strong winds from ice patches to surrounding snow areas. (3) Weathering of, and thus destruction of, meteorites is less severe under Antarctic conditions compared with more moderate climates with a greater concentration of liquid water available. This allows for the build-up of high meteorite concentrations on the surface of stagnant ice fields.

Mean survival times of meteorites recovered in Antarctica are much longer than those from warm or wet areas. Terrestrial ages (the time elapsed since a meteorite's fall to Earth) of up to 2 million years have been observed for Antarctic stone meteorites.

Before classification a name is given to each Antarctic meteorite. It consists of a geographical locality term, a two-digit number specifying the austral summer season of collection, and a number of two or more digits specific to the individual specimen (e.g., Allan Hills 84001).

During the last decades Antarctic meteorites became very important in the fields of cosmochemistry and planetology. The Antarctic collection represents a relatively unsorted and unaltered sample of what has fallen to Earth over a long time span. Several new meteorite types have been discovered. The most prominent example is the detection of the first lunar meteorite in 1981. By 2004 thirteen additional rocks from the Moon had been found on different Antarctic ice fields. Furthermore, eleven out of thirty-two known Martian meteorites were recovered in Antarctica.

There is no general agreement regarding the causes of differences in type frequencies, textures, terrestrial ages, and mass distributions among Antarctic and non-Antarctic meteorites. It is unclear whether these variations are due to terrestrial processes like weathering and contamination or whether they are of preterrestrial origin.

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See also **Glacial Geology**

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METEOROLOGICAL OBSERVING

Antarctica covers an area about the size of Europe. It rises steeply from sea level at the coast to a vast ice plateau reaching above 4000 metres and covering more than half the continent. Most manned stations are at coastal sites, so their weather is not a true representation of the continent as a whole, as they are much milder due to the influence of the sea. Automatic stations are much more widely spread across the continent and give a broader picture of the meteorology.

The weather varies enormously over this large area. Depressions cannot penetrate far inland and the interior receives the equivalent of only 50 mm rainfall each year—about as much as the Sahara desert. The high altitude of the Polar Plateau and the long winter night make it the coldest place on Earth. The northernmost coastal regions have mean summer temperatures just above freezing, whilst summer temperatures at Amundsen-Scott Station average –28°C. Even the warmest temperature ever reached there is only –14°C. Winter temperatures for the Antarctic Peninsula stations are highly variable depending on where the weather has come from. Northerly winds bringing down air from midlatitudes can push temperatures above freezing, whilst southerly winds from the continental interior can send the temperature plunging below –20°C.

Along the Antarctic Peninsula most stations have recorded significant warming over the last 50 years. Vernadsky station (formerly Faraday or Argentine Islands), with a continuous record going back to 1947 and further data back to 1944, shows the most significant trend. Here the average warming is 0.056°C per year. Elsewhere over the continent trends are variable, with perhaps a bias towards slight autumn cooling and slight winter warming. Global atmospheric models do not suggest that there should be any large warming over the Antarctic Peninsula in response to increasing greenhouse gasses, and it is suggested that the warming is a response to changing ocean currents, which have reduced the amount of sea ice on the western side of the Peninsula.

Meteorological observations are made regularly throughout the day at most manned stations. Surface temperature, humidity, sunshine, pressure, wind speed, and direction are largely measured by automated instruments, but an observer is needed to estimate the visibility and the amount, type, and height of clouds, although automatic instruments are being introduced. The observer also needs to keep note of the weather: rain, snow, fog, gale, etc., as well as more unusual phenomena: diamond dust, halos, mirages, and the aurora australis.

The cold atmosphere of the Antarctic makes it a good place to see some of the more unusual meteorological phenomena. Halo phenomena are caused by reflection and refraction of light from the Sun or Moon by ice crystals in the atmosphere. They may take the form of rings, arcs, pillars, or bright spots. Haloes can be seen from most countries and are normally formed by high, thin clouds. In the Antarctic, another phenomena called diamond dust also produces them. Here, because the air is so cold, ice can crystallize out of clear air near the ground. As the crystals tumble slowly to the ground they catch and reflect the sunlight like thousands of tiny diamonds.

At more than a dozen stations balloons are launched once or twice a day, each carrying a package of meteorological instruments known as a radiosonde. The instrument package signals back the temperature, humidity, and pressure to an altitude of over 20 km, with wind speed and direction found by tracking the package with GPS sensors. Special ascents are sometimes made to help study the lower part of the atmosphere called the troposphere, where weather systems are active. These include flights to investigate very stable conditions in the lowest layer, which mainly occur during the winter and other flights to study, for example, depressions forming in the Weddell Sea. Such studies are augmented by atmospheric profiles measured using captive packages carried aloft by kites or blimps. Further studies are made using instrumented aircraft, for example to study the composition of clouds in situ.

A meteorologist at an Antarctic station would start a typical day at 8 am, and complete a meteorological report during the morning. On an average summer's day at a coastal station it would be daylight and the weather might be slight snow or sleet, with overcast skies, light winds, and the temperature near freezing. By contrast, during the winter it would be dark, and with clear skies there would be a hard frost and temperatures around –30°C. The observations are checked, then coded into numeric form and sent via satellite to meteorological centres outside Antarctica. Other tasks are making measurements of snow accumulation, observing the ozone layer, and making measurements of atmospheric aerosol. All types of meteorological observations are conducted regularly throughout the day. In addition to the scientific work, the meteorologist has to help with the general base work.

History

Meteorological observation in Antarctica has a history as long as the exploration of the continent, and logs of the exploring ships and whalers give an early account of the continent's weather. For example, Edmund Halley in 1700 whilst off South Georgia encountered icebergs and noted that he was "In imminent Danger to loss our ship and lives, being Invironed with Ice on all Sides in a fogg soe thick, that we could not see it till [the ship] was ready to strike against it." James Clark Ross made the first systematic meteorological observations during his voyages with the *Erebus* and *Terror* in 1841–1843, and discovered that the mean atmospheric pressure was significantly lower than at the equivalent northern latitudes.

Continuous regular observation began at the beginning of the twentieth century with the establishment of a station at Scotia Bay, Laurie Island, in 1903. The Scottish National Antarctic Expedition, led by Dr. William S. Bruce, commenced observations in February 1903. The station was transferred the following year to the Argentinean Servicio Meteorologico Nacional, which has been running it ever since as the station Orcadas. In the following years further short-lived stations were set up as bases for exploration, for example Jean-Baptiste Charcot wintered at Petermann Island in 1909, and the British Graham Land Expedition (BGLE) set up several stations in 1935. The next big wave of station establishment came with the Second World War. Fears that the Germans might establish U-boat stations on the Antarctic Peninsula led to the establishing of British bases at Deception Island, Hope Bay (the record continues at nearby Esperanza), and Port Lockroy. All made meteorological measurements. Further stations around the continent were set up in the postwar period, such as Mawson, which was established by Australia in 1954.

The International Geophysical Year of 1957–1958 (IGY) provided a big impetus towards setting up continuously operated stations and more than forty were set up, of which more than a dozen are still operating today. This was the peak of manned observation in Antarctica, and since then the number of staffed stations has declined, though this is offset by an increasing number of automatic stations. A further boost to the observing network will take place for the International Polar Year of 2007–2008.

Research ships on their voyages to the coastal stations regularly make meteorological observations, usually every 6 hours. These are supplemented by drifting buoys that are often deployed to study the motions of ice floes. Further observations come from polar orbiting satellites; these can provide images in a variety of wavebands, and also provide temperature and other profiles. All types of observation are now used in global forecasting models.

Observational Problems

Although many of the observations made in Antarctica are done in exactly the same way throughout the world, some additional problems are encountered. Temperature measurements are often made using the Stephenson screen, or variations of it. These shield the thermometer from direct solar radiation and from precipitation falling on the thermometer. In low wind speeds in summer, the radiation reflected from the high albedo surface can give anomalously high readings, whilst under clear skies in winter the reverse can occur. Many stations use aspirated screens, where air is sucked over the thermometer bulb at a constant flow rate, to provide more consistent data. In blizzard conditions a screen can fill with drifted snow, giving a uniform temperature environment unless it is quickly cleared. Some protection can be afforded by the use of snow boards, which temporarily block the louvres whilst the blizzard is in progress.

Measuring the precipitation itself can be difficult. The snow is generally dry and what falls into a standard rain gauge just as easily blows out again. Similarly, precipitation that has fallen elsewhere or at a previous time can be blown around by the wind and into the gauge. Specially designed snow gauges provide a partial solution and another is to measure the depth of freshly fallen snow, and assume that in the long term there is a balance between transported and falling snow. Electronic precipitation detectors using scintillation in an infrared beam are now being deployed in Antarctica, and combination of the outputs of two detectors at different heights may provide the necessary discrimination between precipitation and transport.

Wind measurements were traditionally made using large, heavy-cup anemometers. These required a significant wind speed before they started turning and did not respond well to gusts. They were replaced by anemometers with lightweight plastic cups that performed better in these circumstances, but which

Weather Data for Selected Stations

	Cambridge, UK	Grytviken	Signy	Argentine Islands	Rothera	Halley	South Pole
Latitude, longitude	52° N, 00° W	54° S, 37° W	61° S, 46° W	65° S, 64° W	68° S, 68° W	76° S, 27° W	90° S
Annual mean temperature (°C)	9.9	1.8	–3.5	–2.5	–4.9	–18.5	–49.0
Mean summer temperature (°C)	16	5	1	0	0	–7	–28
Mean winter temperature (°C)	4	–1	–9	–6	–11	–28	–59
Extreme maximum temperature (°C)	35.6	26.3	16.2	11.7	7.2	4.5	–14
Extreme minimum temperature (°C)	–17.2	–19.4	–39.3	–43.3	–37.6	–55.3	–83
Days with snow or sleet	20	195	280	250	225	175	Most days*
Days with rain	145	180	95	85	30	0	0
Hours of sunshine	1490	1200	550	840	1100	1450	2830
Percentage of possible sunshine	34	28	13	19	25	34	65
Mean wind speed (knots)	6.8	8.1	13.8	7.5	12.0	13.3	10.8
Maximum mean wind speed (knots)	54	50	59	50	58	62	36
Maximum gust (knots)	85	96	115	73	77	80	48
Number of gales per year	1	7	60	10	70	40	3

*Precipitation at South Pole is mostly in the form of diamond dust or ice crystals. The total snow accumulation is around 280 mm a year.

frequently became coated with rime deposited from fog, and hence underrecorded wind speeds. Propeller-type combined vanes and anemometers suffer less from rime, but can suffer mechanical failure. The modern replacement is the sonic anemometer, which can measure both wind speed and direction, can be heated to dispel any riming, and has no moving parts apart from the ultrasonic source.

Sunshine amounts are traditionally measured using the Campbell-Stokes recorder, a sphere of glass that focuses the sun's rays onto a fixed card where they burn a hole in bright sunshine. This suffers from a universal problem of overrecording in patchy cloud conditions, and also experiences another problem in polar latitudes, where there can be 24 hours daylight. In high southern (or northern) latitudes two recorders have to be mounted back to back to measure sunshine throughout the long day. Modern electronic records get around both problems and allow continuous recording.

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See also **Amundsen-Scott Station; Antarctic Peninsula; British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); British Antarctic Survey; British Graham Land Expedition; Bruce, William Speirs; Climate; Deception Island; French Antarctic *(Pourquoi Pas?)* Expedition (1837–1840); International Geophysical Year; Ozone and the Polar Stratosphere; Precipitation; Ross, James Clark; Scottish National Antarctic Expedition (1902–1904); South Georgia; Temperature; Wind**

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MICROBIOLOGY

Microbiology is the study of microorganisms—microscopic forms of life that are ubiquitous in the biosphere and form an important component of Antarctic terrestrial, freshwater, and marine ecosystems. Their key functional role within Antarctic communities is in primary production, decomposition, and nutrient cycles. Microorganisms play an important role in global nutrient cycling, for example, in the nitrogen cycle. Abiotic transformation of nitrogen is extremely slow, whereas microbial oxidations and reductions are rapid, so microorganisms are responsible for the fixation of nitrogen and for the nitrification and denitrification of nitrogen compounds. They are also key components of the other nutrient cycles including the carbon and sulphur cycles and in the mineralization of organic waste, for example penguin and fur seal excrement.

Microbiology as a science has been conducted in the Antarctic since the first half of the twentieth century, although there has been significant understanding of Antarctic microbial ecosystems only in the last 20 years, as techniques developed elsewhere have been applied to Antarctic ecosystems. This is primarily because microbiology progresses in significant bursts largely associated with the development of new techniques and the application of new technologies, such as the invention of the microscope, the development of specific cultivation techniques, the invention of new methods for micromanipulation, novel biochemistry such as the polymerase chain reaction (PCR), or more recently through the application of *in situ* methodologies.

Microorganisms can be classified into a number of kingdoms or phyla. These classifications are not all universally agreed, but broadly consist of viruses, Archaea, Eubacteria, Fungi and Microsporidia, Alveolata, Stramenopila, Rhodophyta, green algae, and Protista. The viruses are relatively simple obligate intracellular parasites, and generally consist of either a single or double stranded DNA or RNA molecule, associated with a number of specific viral proteins. The Eubacteria are single-celled organisms lacking any membrane-bound organelles, including a nucleus, and are typically <10 μm in size. In the Antarctic, this group is largely represented by Cyanobacteria, Proteobacteria, and Gram-positive bacteria. The Archaea are another prokaryotic group like the Eubacteria but with uniquely structured membrane lipids; they are a very diverse group, both in terms of their morphology and their metabolic activity. The Fungi are nonphotosynthetic eukaryotes with chitin-containing cell walls, and include the generally unicellular yeasts. Algae have been separated into three phyla with the red algae placed in the rhodophyta, the green algae in the viridiplanta, and the brown algae in the stramenopila. This last phylum also includes a diverse range of microbial life, including the diatoms and water moulds. The classical protozoa are currently split between a number of phyla and unassigned subphyla. There appears to be considerably less endemism and geographic restriction of micoorganisms than there is for larger organisms, and in broad terms the colder regions of the world are populated by the same genera of microorganism as found elsewhere, and include all microbial processes, but these processes take place at a slower rate than in warmer environments—stopping altogether when cellular water freezes.

Microorganisms are very different from animals and plants, with a biomass many orders of magnitude smaller than any macroscopic metazoan or higher plant. However, an equally important characteristic of free-living microorganisms is their extraordinary abundance. Commonly, much greater numbers of bacteria and protozoa are found in natural systems than larger organisms. Microbial population sizes in the natural environment are, in relative terms, astronomically large, with more than 1,000,000 bacteria or 1000 flagellated protozoa per millilitre of freshwater. High abundance also has important implications for natural dispersal, because it raises the probability that representatives of each species may, for purely statistical reasons, be frequently transported—even over large distances. Microbial species may, potentially, be ubiquitous. They may be carried on the feet and damp feathers of penguins and other birds, or, like fungal spores, and even bacteria, be carried in wind or convection currents high into the atmosphere and transported thousands of kilometres. Less dramatically, microbes will be continuously transported in melt waters and in innumerable other ways. As has been found elsewhere, when there are no effective barriers to the dispersal of free-living microbes, speciation is rare. The total number of novel microbial species will be relatively small, and so local species richness will, as a general principle, reflect global species richness. However, this has yet to be established for the Antarctic, where the vast majority of microorganisms have yet to be identified.

Particularly abundant groups of microorganisms identified in microbiological studies in the Antarctic include the cyanobacteria (photosynthetic bacteria), lichens (symbiotic associations between a cyanobacterium or an algae and a fungus—particularly well adapted for life in the most extreme environments as the symbiosis makes them widely trophically independent of substrate type), psychrophilic bacteria (bacteria which grow between 0°C and 20°C and have an optimal growth temperature of 15°C or less), psychrotolerant bacteria (bacteria with an optimal growth temperature between 0°C and 5°C and at a maximum above 25°C), and psychrotrophs (can grow at low temperatures such as 0°C, but have an optimum in the mesophile range of 20°C–40°C). Obligate psychrophilic bacteria are unable to grow above 20°C, facultative psychrophiles are capable of growth at low temperature, but also grow above 20°C. Among cold-adapted microorganisms, psychrotrophs tend to dominate in environments that undergo thermal fluctuations. True psychrophiles have a more restricted growth range and are found in permanently cold habitats. However, even in permanently cold environments, >50% of the bacteria are not psychrophilic. In global terms, psychrotrophs are much more widely distributed than psychrophiles. From permanently cold habitats in the polar regions, the psychrophilic alga *Raphidonema nivale* and the fungus *Sclerotinia borealis* have been isolated. Among terrestrial psychrophiles are members of the genera *Pseudomonas, Cytophaga,* and *Flavobacterium* (each commonly encountered in the freshwater lakes of Signy Island).

Antarctic microorganisms include autotrophs (organisms that are able to use simple carbon compounds such as carbon dioxide gas as a source of carbon, and light as a source of energy), heterotrophs (feeding on living or dead organic matter), and chemoautotrophs (obtaining energy by oxidizing simple organic molecules). Many microorganisms, which grow and survive in extreme Antarctic environments, could be classed as extremophilic. Extremophiles are microorganisms that live under extreme conditions, where they not only tolerate the extreme but have an obligatory requirement for it, as they are frequently associated with adaptations to dry, nutrient poor, osmotic, and high light stress including high-ultraviolet-light environments, and compete badly with more cosmopolitan genera under more benign conditions elsewhere. Microorganisms show a variety of different tolerances to the degree of freezing and have evolved a number of different methods for dealing with the problem. These include spore formation (a more resistant form in the life cycle); influencing the external environment, such as the production of extracellular materials that reduce or prevent ice formation; increasing cell permeability and changing membrane fluidity to withstand expansion and contraction stress brought about by water loss; and rehydration or increasing solute concentration to depress the freezing point of intracellular fluid. Other factors that affect microbial growth in the Antarctic include substrate availability (including both growth substrates and terminal electron acceptor availability), the presence of competitors and antagonists, light availability (in terms of its intensity, spectral composition and duration—particularly for the autotrophs), high-energy ultraviolet radiation damage, temperature, pH (hydrogen ion concentration), pressure, osmotic potential and water availability, predation, dissolved gases, the presence of organic matter, micronutrients, and space available for growth.

A particularly important group of microorganisms that have not received much attention are the viruses. Considerable evidence exists to suggest that viruses are key components of many microbial communities, yet relatively little attention has been paid to their role in either terrestrial or aquatic Antarctic ecosystems. Elsewhere, studies of virus communities in microbial ecosystems have demonstrated that viruses can influence community structure, productivity, function, nutrient cycling, and food-web interactions. It has also been suggested that viruses have a role in the maintenance of biodiversity, the control of population size, the clonal composition of populations and genetic exchange. In spite of this, very few studies of viruses in Antarctic ecosystems have been conducted to date, yet the subject has enormous potential for answering some of the very fundamental questions of microbial ecology.

Habitats for microbial growth in the Antarctic are surprisingly diverse. The Antarctic continent is thermally and biogeographically isolated from the subtropics by the Antarctic Circumpolar Current, a global ring of cold water that contains complex frontal features and upwelling and downwelling cells. The Polar Front separates the Atlantic, Indian, and Pacific oceans from the Southern Ocean and the temperature discontinuity associated with it can be a barrier to migration and free flow of organisms. Thus, the Southern Ocean has its own unique characteristics; for example, upwelling of nutrient-rich water results in primary productivity that constitutes nearly one-third of the oceanic total. About two-thirds of the silica supplied annually to the ocean is removed by siliceous microorganisms in the Southern Ocean. The Southern Ocean can be subdivided into a number of characteristic environments: the pelagic and benthic environments, both deep-sea (with associated hydrothermal vents and cold seeps) and shallow areas including the sediment. The icebergs, seasonal and permanent sea ice, and ice shelves all contain microorganisms (for example, *Polaromonas vacuolata*) and harbour their own sets of microbial niches including melt pools. The bacterioplankton of polar seas is of about the same density as that of temperate waters, usually within an order of magnitude of 10^6 cells mL^{-1} and correlated with phytoplankton biomass. It consists of both psychrophilic and psychrotolerant bacteria. Organic substrate utilization increases by 30% when the temperature is raised from about 2°C to 5°C, but is inhibited above this. Although the overall metabolic activity of the bacterioplankton is heterotrophic, the biochemical details have yet to be established. The near-shore marine ecosystem includes shallow seas, nutrient upwelling, freshwater and nutrient run-off from the land, and includes rocks and rudimentary soils with varying degrees of salinity and marine nutrient input. On rocky shores, microhabitats may provide shelter from wave action, desiccation, predation, and insolation. Sediments may contain gradients of reducing activity if they become anaerobic. Marine mammals, such as fur seals, and birds, such as penguins, come ashore and deposit marine-derived nutrient into the Antarctic terrestrial system.

Terrestrial habitats for the growth of microorganisms are diverse and microorganisms have been found to exist in the upper layers of the ice sheet, and microorganism fossils have even been found in deep ice cores. Antarctica is the fifth largest continent, comprising about 10% of the Earth's land surface area. It is the highest, driest, windiest continent, yet contains a surprising diversity of habitats for microbial colonization and growth. Specific habitats include soils, some of which are saturated with minerals (soils can also be separated according to the presence or absence of vegetation—the microbiota of vegetated soils generally resembles the microbiota of soils everywhere), rocks, lithic, including hypolithic and endolithic communities (for example *Gloeocapsa* sp.), chasmolithic (in the cracks and fissures of weathered rocks), cryptoendolithic (in the interstices of porous rocks), sediments (both oxic and anoxic), cryoconite holes, ice, snow, meltwater, freshwater lakes, saline lakes, hypersaline lakes, streams and flowing waters, regions subject to volcanic activity (for example, Mount Erebus), and the air itself. Another notable habitat is subglacial lakes: accretion ice forms, and above Lake Vostok almost 4 km below the ice surface, both prokaryotic and eukaryotic microorganisms have been found in a spectrum of sizes and morphologies. These include heterotrophic bacteria in modest numbers, but with a comparatively low diversity including the alpha and beta proteobacteria; spore-forming bacteria, for example, *Bacillus* sp.; low and high G + C content Gram positives; Actinomycetes; Cytophaga-Flavobacterium-Bacteroidetes group; fungi; yeast; and microalgae. Strong gradients in both physical and chemical parameters within the environment produce sharply defined zonation in many Antarctic microbial communities. Superimposed on this spatial heterogeneity, there is also a temporal heterogeneity with a strong degree of seasonality (which can vary from 24 hours of daylight to 24 hours of darkness). Indeed, in many Antarctic limnetic systems, microorgansisms may be enclosed beneath an ice cover all year round (and therefore subject to a high degree of chemical and physical stratification, leading to a large number of potential microbial niches for colonization). The nutrient, poor status of the vast majority of Antarctic ecosystems, together with constant low temperatures, a short ice-free growing season and, of course, the Antarctic isolation factor, significantly influence microbial biodiversity in these systems.

Specific techniques used in the study of Antarctic microbiology are diverse and include direct microscopy, which can involve the use of specific stains, pure culture, direct isolation, isolation following enrichment, cultivation, preservation, direct culture under a variety of temperature regimes (which specifically excludes viable but yet to be cultivated microorganisms), serological methods, substrate utilization tests, antibiotic sensitivity and assay tests, molecular biology (particularly for taxanomic studies—the analyses of 16S rRNA and the use of PCR have become common in the investigation of the spatial distribution of microbial taxa in the natural environment that have not been grown in culture and is increasingly applied to Antarctic communities) and the use of fluorescent probes. With the advent of molecular identification techniques based upon the 16S rRNA gene, sequence information has become widely available for nearly all of the validly described prokaryotes. As this information grows, the understanding of evolution and potential endemism in Antarctic microorganisms is growing. Indeed, the importance of the cyanobacteria in Antarctica could be seen as an analogue for the early evolution of life on Earth and could thus be a good proxy for its study.

Key microbiological research sites in the Antarctic tend to be those readily accessible from established research stations, for example, Alexander Island from Rothera research station (UK), the Dry Valleys from McMurdo research station (USA), the Vestfold Hills from Davis research station (Australia), the Larsemann Hills from Zhongshan, Progress or Laws bases (China, Russia, and Australia respectively), King George Island (various) or from ships on marine cruises. An important feature of Antarctic microbial communities is that they form the end point of an environmental continuum from the tropics to the poles.

The microbiological research activity conducted in the Antarctic includes the impact of humans and human activity on the Antarctic environment (as humans have only recently been active to a significant degree on the continent), propagules from non-Antarctic sources can potentially arrive on the boots of expeditions and scientists, in the ballast tanks of ships, and through the waste material generated by human activity. In addition, human populations on remote Antarctic research stations can be used in medical research such as for epidemiological studies. Biotechnology is important in the potential for exploitation of Antarctic microorganisms or indeed microbial communities such as established biofilms for low temperature activity of enzymes, as a source of novel metabolism for bioremediation or low temperature biotransformations. A specific example is the mechanism by which bacteria from Antarctic sea ice produce polyunsaturated fatty acids. The study of Antarctic microbial communities may offer new insights into the molecular basis of cold adaptation, including cold-adapted enzymes such as psychrophilic carbohydrase and antifreeze proteins, a better understanding of the microbial cold stress response, overwintering strategies, protective pigment synthesis, and the response to ultraviolet radiation damage. The presence of the Antarctic ozone hole, which expands and contracts seasonally, ensures that Antarctic microorganisms receive unusually high doses of ultraviolet radiation for extended periods.

The relative isolation of the Antarctic continent makes it ideal for the study of microbial biodiversity, biogeography, evolution, migration and gene flow (for example, the transport of microbial inocula by birds), genetic variation, population genetics, and environmental genomics. It has been suggested that Antarctic ecosystems are of relatively low complexity with short food chains and limited biodiversity. Whilst this is still a subject of debate, if it is proved to be the case, Antarctic microbial communities would form ideal models with which to study ecological interactions, food web dynamics and microbial predator-prey interactions. In its most simplified case, the lakes on Signy Island, for example, do not contain fish (removing one of the key higher predators). Elsewhere there are no higher plants (such as trees) or in many cases animals. Such systems are dominated by the microbial loop.

It has been shown recently that the Antarctic Peninsula is subject to relatively rapid temperature rises, and so forms an ideal place to study the effects of global climate change, particularly with respect to changes in patterns of biodiversity and nutrient cycling. The conditions under which the microbial communities exist may act as a proxy for studies of the potential for life elsewhere in the solar system such as Mars or Europa, and indeed, for the development and testing of novel life detection systems. The potential exists within the Antarctic for the discovery of novel microorganisms. With an estimated 1,000,000–100,000,000 prokaryotic species believed to exist, to date less than 1000 have been described. So we are a very long way from a complete species inventory. The Antarctic provides a number of perhaps unique niches for the colonization of potentially highly specialized microorganisms, and these include subglacial lakes (such as Lake Vostok), microbial mats, endolithic communities, and even historic expedition huts (which have been found to harbour wood-decaying fungi). As evidenced by the discovery of Tomato mosaic tobamovirus in an ice core from Greenland, the Antarctic may act as a seed bank, the ice containing propagules of viable species that might be released following a rise in global temperature and an accelerated melting of the polar ice caps.

Bipolar comparisons in microbiology offer important insights into which species are ubiquitous in their global distribution or which might be endemic to a particular environment, especially as the Arctic consists of an ocean surrounded by land masses, whereas the Antarctic consists of a land mass surrounded by an Ocean. By understanding anthropogenic changes in the Antarctic ecosystem and comparing them to analogous communities elsewhere on the globe such as high altitude, Alpine, or permafrost environments, scientists can deduce whether particular human activities such as industrial processes and nuclear power are having a local or global impact (as there is no industry in the Antarctic). Bipolar comparisons have already been made between bacterial communities in pack ice, sea ice, marginal ice zones, sea water, mat forming cyanobacteria, and deep-sea sediments.

Antarctic microbiology, therefore, is a field that has been growing rapidly over the last 20 years, and as new studies are published, the subject is increasingly contributing to understanding the role and function of microorganisms in both low temperature and extreme environments, including information on nutrient cycling, gene flow, evolution, biogeography, biodiversity, and ecosystem function.

David A. Pearce

See also **Algae; Antarctic: Definitions and Boundaries; Antarctic Peninsula; Archaeology, Historical; Biodiversity, Terrestrial; Biogeography; Circumpolar Current, Antarctic; Climate Change; Cryconite Communities; Ecosystem Functioning; Exobiology; Fungi; Gene Flow; King George Island; Lake Vostok; Lichens; McMurdo Station; Mount Erebus; Oases; Ozone and the Polar Stratosphere; Penguins: Overview; Polar Front; Protozoa; Soils; Streams and Lakes; Subglacial Lakes**

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MINERALIZATION

Antarctica is often called the El Dorado or the treasury of the world. Why is there such a strong belief in the mineral wealth of Antarctica? Two reasons might be mentioned:

1. Antarctica ($\sim$11.9 million km^2) is larger than Europe or Australia. Theoretically, with respect to the size of other continents and the number of mineral deposits they have revealed so far, there should be more than 900 deposits in Antarctica.
2. Antarctica's mineral wealth is still untouched; the resources have not yet been mined as they have been for centuries on all of the other continents.

Human activity in the Antarctic is regulated. According to Article 7 of the Environmental Protocol to the Antarctic Treaty, *any activity relating to mineral resources, other than scientific research, shall be prohibited*. This is valid for at least 50 years after coming into force in 1998. Besides this political ban on mining, there are numerous reasons for scepticism concerning the feasibility of exploitation. At present, any mineral showings or deposits can only be appraised as not economically exploitable. The Antarctic is outstanding in many aspects: It is the coldest, windiest, most remote, inaccessible, and hostile continent. The shelf is very narrow and deep. For comparison: The Arctic shelf down to 500 m water depth is 4.4 times larger than the Antarctic shelf. Less than 2% of the Antarctic continent is free of ice: average ice thickness, 2100 m; maximum measured, 4776 m. Antarctica is the geologically least known and environmentally best protected continent. All these superlatives have a negative impact on any exploration and exploitation. As no exploration or mining can be conducted through the ice cap, the number of 900 theoretical deposits has to be reduced drastically to about 20 "ice free" deposits.

The Dufek Massif south of the Ronne Ice Shelf is probably the second largest layered intrusion (after the Bushveld Massif). It is thus prospective for nickel, cobalt, chromium, vanadium, and platin group elements (PGE), although the base of the intrusion, the most prospective part for these metals, is not exposed.

The Antarctic Peninsula, which represents geologically the southward extension of the Andes, is prospective for nonferrous metals like copper, silver, gold, and molybdenum. Small showings have been described from the Antarctic Peninsula (e.g., the low-grade porphyry mineralizations of copper, iron, lead, and molybdenum sulfides or oxides in alteration zones of the Copper Nunataks [Lassiter Coast], or gold and silver mainly as accessory minerals in stockwork and vein mineralizations on Stonington Island). Although the Antarctic Peninsula is considered part of the Andean province, where large porphyry copper deposits (e.g., El Teniente, Chuquiquamata) occur, one has to emphasize that the Cenozoic tectonic development of the Andes and the Antarctic Peninsula differs considerably.

Coal is known in the Transantarctic Mountains and the Beaver Lake area (East Antarctica), and iron ore in the Prince Charles Mountains. Both bulk commodities are of absolutely no commercial interest. Only large deposits with high-grade ores of high-value commodities could have a chance to be above the pay limit in future, but these deposits are not yet discovered.

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See also **Antarctic Peninsula, Geology of; Coal, Oil, and Gas; Protocol on Environmental Protection to the Antarctic**

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MINKE WHALE (ANTARCTIC MINKE WHALE)

Name

Although minke whales had been classified as only one species of *Balenoptera acutorostrata* until the late 1990s, its taxonomy has recently been rearranged. Two separate species have now been recognized in the Southern Hemisphere. Minke whales in the Antarctic are now recognized as *B. bonaerensis* with the common name of "Antarctic minke whale." Elsewhere in the Southern Hemisphere, the dwarf minke whale is the recognized species, and this is currently classified as a subspecies of the Northern Hemisphere minke whale, *B. acusutara.* However the taxonomic status of these species is still pending. The dwarf minke whale can be recognized from white pigmentation on the shoulder that is absent from the Antarctic minke whale. The Antarctic minke whales are mainly reviewed here.

General Appearance

While Antarctic minke whales are the smallest species among rorquals (general name of genus *Balaenoptera*) in the Antarctic, they grow up to 10 m in body length. However, usually body lengths at attainment of physical maturity are 9.0 m and 8.5 m for females and males respectively. Approximate body weights at that stage are 8.0 and 7.0 tonnage for females and males respectively.

Compared with other rorquals, the minke whale has a relatively small, triangular-shaped head (25% to body length) and pointed rostrum. The body color is black or grey and white ventrally. A pair of crescent-like streamline marks of pale color runs from the ear to the anterior base of the flipper on both sides of the shoulders. Similar streaks of slightly weaker color can sometimes be seen above the posterior parts of fore-flippers. The most characteristic feature is that the Antarctic minke whales lack the white color patch on the fore flipper, which is common coloration in other minke whales of both hemispheres. The dorsal fin is large and curved. Tail flukes are half-moon shaped with a central notch on the posterior margin. The tail flukes are black on the dorsal surface and usually white on the ventral surface. On the throat, there are about forty-five ventral grooves that run from the tip of the lower jaw to just anterior of the umbilicus.

The Antarctic minke whales have a series of 260–360 baleen plates in the palate, on both sides of the inner surface of the rostrum. The maximum length of these plates is about 30 cm, with the longest plates occurring at about one-third along the length of the plate series from the posterior. The outer colorations of the plates are not bilaterally symmetrical. The plates are creamy white with a black belt at outer margins of all the plates on the left side and the posterior two-thirds of the plates on the right side. The plates of the first one-third of the right side are entirely creamy white.

Population Status, Distribution, and Habitat Use

The minke whale occurs mainly to the north of the Polar Front (located at 55° S–60° S) and the Antarctic minke whales is found to the south of the convergence, especially in the region 60° S to ice edge in the middle of summer. Although minke whales are especially highly concentrated in some localities such as the southern Ross Sea, they are found throughout Antarctic waters. Minke whales migrate regularly to high latitudes in summer, probably mainly to feed along ice edge where there are nutritionally rich areas. Mature/pregnant females have a greater tendency to be in waters close to the ice edge.

The population status has been assessed by scientific committee of the International Whaling Commission (IWC) through its international research project of IDCR (International Decade of Cetacean Research) and subsequently by SOWER project (Southern Ocean Whale and Ecosystem Research). Generally, the Antarctic minke whales are considered to be the most robust whale stock in the Antarctic. The IWC Scientific Committee agreed an abundance estimate of the Antarctic minke whales of 760,000 individuals south of 60° S based on the second circumpolar IDCR assessment cruises in 1985–1986 to 1990–1991. The third circumpolar survey was completed by the 2003–2004 season and the assessment is now being conducted using those data.

Life History

Breeding occurs at the low-middle latitudes in the austral summer. The breeding grounds are thought to be in waters off the northeastern coast of Brazil, western coast of South Africa, and northeastern and eastern coast of Australia. Antarctic minke whales are born at 2.85 m in average body length after 10.5–11 months gestation. There is no bias in the foetal sex ratio and the litter size (number of fetuses conceived) is invariably 1.0. The mean calving interval is 1.28 years (or annual pregnancy rate of 0.78). Most of the calves probably wean at about 3 to 4 months of age at a body length of about 4.5 m.

Lengths at sexual maturity are 7.9 m and 8.2 m for males and females respectively, which appear not to vary with respect to nutritional condition. Age at sexual maturity has changed with nutritional condition: in the 1940 cohort it was 11–12 years, but had declined to 7 years in the 1970 cohort. This decrease took place before exploitation in early 1970s and was thought to be the result of an increase in the growth rate of the minke whales due to declines of their ecological competitors including other rorquals. Growth of body length continues until 25 years for both sexes. The maximum known ages among the samples is 50 years.

Social Structure

There has been no direct observation on both mating and calving and therefore little is known about breeding behaviour, though minke whales are generally thought not to be highly social animals. In the Antarctic, the minke whales usually occur with a small school size consisting of two or three animals, although there are some reports of larger aggregations up to 400 individuals.

Diet and Tropic Interaction

The Antarctic minke whales mainly feed on euphausiids and are highly dependent on the Antarctic krill *(Euphausia superba)* in the main feeding ground. Their feeding activity is thought to peak in early morning, probably near daybreak. It is estimated the minke whales' daily food consumption corresponds to 4%–5% of total body weight.

As mentioned, minke whales may compete ecologically with other rorquals for food and habitat, and this may have been the underlying factor causing changes in the age at sexual maturity of the minke whales.

Economic or Nutritional Use

Exploitation of the Antarctic minke whales has been regulated by the IWC and there has been no sign of depletion. Although several countries such as Russia, Brazil, South Africa, and Japan have taken some minke whales in recent years, substantial exploitation occurred between 1971 and 1987. Japanese and Russian whaling fleets took annual catches of 4969–7900 through this period.

Because the IWC adopted a moratorium on commercial whaling for all stock of large whales in 1982, there were no commercial harvests of minke whales after 1987–1988 in the Antarctic. In that year, Japan started a specially permitted research program (JARPA) that included the harvest, for scientific purposes, of up to 330 minke whales per year. The number taken under the JARPA program was increased to 440 individuals after 1995–1996.

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See also **International Whaling Commission (IWC); Polar Front; Whales: Overview; Whaling, History of; Zooplankton and Krill**

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MOLLUSCS

Currently, more than 700 hundred species of molluscs are described from Antarctic waters, and, as Antarctic exploration continues, more species are discovered every year. All eight molluscan classes have been recorded. The pelagic realm is inhabited by squid, vampyrimorph octopodi, and a few ophistobranch gastropods, but those most commonly seen by human visitors to the region are likely to be pteropods swimming in surface waters. The benthic realm contains a diverse malacofauna: spiky, wormlike Caudofoveata and Solenogastres; eight-shelled, armour-plated polyplacophorans (chitons); limpetlike, multigilled monoplacophorans; shelled and shell-less gastropods, bivalves, and elephant tooth–like scaphopods; and eight-legged octopodi. Molluscs can be found from the intertidal, sitting on rocks and seaweed, to the deep sea. The deepest record for a living bivalve collected is from 6300 m. Their abundances can vary from one to several thousands per square metre.

Antarctic shells differ from those more familiar from low latitudes in a number of ways. More than 80% of the shelled species are less than 2 cm in size. The shells are very thin, in small species nearly transparent. One reason for these thin shells might be that shell-crushing predators such as crabs and lobsters are almost absent. Compared with tropical shells, their Antarctic cousins are missing prominent scales, spines, and patterns, not only in shell form but also in colour. Dominant shell colours are green-brown for protobranch bivalves and white for all others; colours like yellow, orange, pink, and purple, as seen in many temperate gastropods like in topsnails, are rare.

Most (~90%) molluscs that are known from the Southern Ocean occur only in this region, that is, they are Antarctic endemics. Molluscs are not evenly distributed around Antarctica. There are hotspots of species richness at the tip of the Antarctic Peninsula and on the eastern shelves of the Weddell and Ross seas. These patterns of species distributions are a result of evolutionary processes in relation to Antarctica's geological and climatological past. Since the cooling of Antarctic waters (about 35 Ma), groups like the edible bivalves Veneridae and Cardiidae (cockles) have disappeared and have only left their fossil remains. Other groups like the carnivore gastropod families Buccinidae (whelks) and Turridae evolved and split into several, specialised genera and species (adaptive radiation).

Typically, reproduction by Antarctic molluscs takes place over a considerable period, and they produce relatively few, large eggs. Many species brood their offspring in special brood pouches and release juveniles. Others, especially gastropods, attach egg masses to the substrate, in which the offspring develops until they hatch as young adults. While comparable reproduction processes take weeks to a few months in tropical and temperate regions, they take a year to several years in Antarctica. Freshly laid egg masses of the Antarctic whelk *Neobuccinum eatoni* were observed in aquaria more than 12 months before juveniles hatched. Antarctic molluscs invest a lot of energy into their offspring. Studying a 1-mm long specimen of the limpetlike monoplacophoran *Leavipilina antarctica,* three juveniles of 0.3-mm shell length were discovered in the tip of the shell. Famously, amongst marine biologists, Thorson's rule concerning the rarity of planktonic development at high polar latitudes was constructed from work on molluscs.

Katrin Linse

See also **Benthic Communities in the Southern Ocean; Deep Sea; Fossils, Invertebrate; Reproduction**

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MOSSES

Mosses belong to the Plant Kingdom Division, or Phylum Bryophyta, which comprises six Classes, of which the Andreaeopsida, Polytrichopsida, and Bryopsida are represented in the Antarctic. Until a recent revision, mosses, and their close allies the liverworts, were both classified as comprising the Bryophyta. However, liverworts are now treated as a separate Division, the Marchantiophyta.

Mosses and liverworts belong to the group of spore-producing plants known as cryptogams (in contrast to the flowering and seed-bearing phanerogams). The fundamental difference between mosses and liverworts is that moss leaves, while tiny, are entire and those of liverworts are variously shaped, from entire and often rounded to bi- or many-lobed; in some genera they have a flat strap-shaped thallus rather than a leafy shoot. Moss leaves generally have a central strand of cells (midrib) that is absent in liverworts. The life cycle of both mosses and liverworts has two stages: a vegetative stage (gametophyte or leafy shoot), which bears the gametangia that give rise to the sexual stage (sporophyte). The latter comprises a spore-producing capsule borne on a short stalk (seta). It is the leafy shoot that is the typical "moss" or "liverwort" plant. Thus the capsule releases spores that germinate to form a branched filamentous protonema from which a leafy gametophyte develops. Male (antheridium) and female (archegonia) structures form on the shoot, sperm cells are released and fertilise the egg cell to form a zygote. This divides by mitosis to form the sporophyte. Meiosis occurs in the capsule resulting in the formation of spores. Bryophytes contain chlorophyll and assimilate carbohydrates for growth through the process of photosynthesis, just as flowering plants do. Their anatomy is very simple and most water uptake is by absorption through their leaves from both ground water and atmospheric water (precipitation and mist). While many species grow in wet or submerged habitats, many also occupy extremely dry habitats, obtaining their moisture from the very rare precipitation events. The latter category is well adapted to extreme conditions of temperature and desiccation.

Growth-Forms

Mosses have two principal morphological forms (growth-forms) comprising many individual leafy and usually branched shoots, the whole structure being referred to as a colony of shoots. Acrocarps (short erect colonies) tend to grow in drier habitats, while pleurocarps (prostrate spreading colonies) generally occupy moist or wet habitats. Amongst the much more prevalent acrocarps are several growth-form variants, such as cushions (with shoots radiating from a central point, typical of rock substrates) and turves (shoots arranged vertically and parallel, typical of soil). Most species are loosely attached to their substrate by a mass of rootlike rhizoids. The pleurocarps grow as a mass of intertwined shoots to form carpets (on wet ground) and finer wefts (in shaded wet rock crevices and overhangs), and usually lack rhizoids.

Physiology

Because of their simple anatomical structure without specialized water conducting tissues (a few species have a rudimentary conducting system), mosses and liverworts derive their water and nutrients passively and uncontrollably through their leaves and stems. Conversely, they have no control over water loss during dry or sunny weather. Nevertheless, Antarctic species are well adapted to their low-temperature environment, often with a very intermittent supply of liquid water, which is essential for fertilization and physiological processes. Carbon dioxide fixation (photosynthesis) and the formation of carbohydrates required for growth and reproduction can take place at low temperatures (the typical optimum being

10°C –15°C), in some species at or just below freezing point. During spells of brilliant sunshine the high solar irradiance, combined with high colony temperature and desiccation, photosynthesis ceases (photoinhibition). Growth is therefore continually being interrupted, and the annual shoot increment is seldom more than a few millimetres. While most mosses are a shade of green, some xeric species growing in very exposed (especially to solar irradiance) habitats are dark colored. These genera (notably *Andreaea, Ceratodon, Grimmia, Schistidium*) synthesise ultraviolet-protective pigments.

Moss reproduction responds to physiological and environmental stress by switching from sexual to asexual means when conditions become progressively less favourable. Relatively few species produce sporophytes, and even more rarely viable spores, although a few do so regularly. The more common method of colonization is by vegetative propagules varying from detached fragments of shoot to specialized structures which develop into new plants.

Species Diversity and Biogeography

Mosses, together with lichens, are the visually predominant terrestrial life form in the Antarctic, particularly in the wetter maritime Antarctic and coastal areas around the continent. However, many species are xerophytes (growing in extremely dry windswept habitats) colonizing rocks and arid soils. A recent revision of the moss flora of the Antarctic, including the South Sandwich Islands and Bouvetøya (climatically and biologically an extension of the maritime Antarctic) describes a total of 113 species, of which about 18 occur in continental Antarctica. Considering the area of the Antarctic biome (biological region), the moss flora is very small; a similar number could be found in 1 hectare of forest or mountain elsewhere in the world. As with the lichens, no Antarctic moss species have common names. Many species have a southern South American or New Zealand distribution, and a number are bipolar. Some of the commonest and most widespread have a cosmopolitan or global distribution (e.g., *Bryum argenteum, B. pseudotriquetrum, Ceratodon purpureus, Pohlia nutans, Sanionia uncinata,* several species of the family *Polytrichaceae*). Many species appear to be very rare in the Antarctic and several are restricted to the unique geothermal habitat associated with volcanic activity at a very few sites (see below).

Throughout the northern maritime Antarctic the current trend of regional climate warming has caused substantial recession of ice field and glacier margins and thickness since the mid-twentieth century. This has revealed many subfossil (a few hundred to several thousand years old) moss turf banks. These have retained their original structure and the component species are still readily identifiable. However, there is no evidence that any species existed earlier in the Holocene that do not occur at present.

Ecology of Moss-Dominated Communities

Few moss species develop pure stands of more than a few square metres, although different groups of mosses, often with associated lichens and occasionally liverworts, typically combine to form distinctive communities. These communities are dependent on the geological nature of the local rock and soils derived from them, degree of shelter and local microclimate, availability of moisture, and soil stability (i.e., free from frost heave activity, erosion, sea bird, or seal impact, etc.). Some species have a wide ecological amplitude (catholic in their habitat preference, such as *B. pseudotriquetrum, Pohlia nutans, Sanionia uncinata*), while a few are very selective and prefer specific environmental conditions or substrates (e.g., *Dicranella hookeri, Philonotis acicularis* associated with steam-emitting fumaroles in volcanic areas; *Muelleriella crassifolia* on rocks within the spray zone of coastal rocks; *Schistidium rivulare* on rocks in streams).

The most extensive stands of moss, sometimes covering more than a hectare, occur in the maritime Antarctic region, with the largest continuous expanse of closed moss vegetation (predominantly *Sanionia uncinata*) being on Aitcho Island, South Shetland Islands. Depending on habitat features, communities dominated by one or more species predominate. Here, in the absence of serious competition from other bryophytes and vascular plants, certain mosses attain virtually monospecific status and develop almost pure closed stands of several hundred m^2; elsewhere, two or more species may codominate. It is a feature of the Antarctic moss flora that no more than a dozen species frequently attain widespread dominance over more than about 25 m^2. However, many species may do so on a small scale by forming almost pure patches of a few m^2 within more complex communities. Habitats with relatively stable conditions tend to have low species diversity, but increasing habitat variability, such as typify fellfield or feldmark (rocky glacial terrain, typically windswept, dry and disturbed by freeze-thaw action, and sparsely colonized by vegetation), and sites of variable small-scale geology (e.g., at Signy Island), lead to increased species diversity both in bryophytes and lichens, and create the most complex communities of the biome.

Wet habitats with impeded drainage in the maritime Antarctic are typically dominated by three carpet-forming pleurocarpous species *(Sanionia uncinata, Warnstorfia fontinaliopsis, W. sarmentosa),* while mildly calcareous seepage areas support, in addition, *Campylium polygamum*. Habitats subjected to moving water (margins of melt runnels, wet rocks, etc.) support large loose cushions of *Brachythecium austrosalebrosum* and *Bryum pseudotriquetrum* and, occasionally in the more northerly region, *Syntrichia filaris*. Seepage areas below melting snow fields in coastal continental Antarctica sometimes support large stands of *Bryum subrotundifolium*.

A unique community type of moist, well-drained rocky hillsides in the northern maritime Antarctic is formed by the tall turf-forming mosses *Chorisodontium aciphyllum* and *Polytrichum strictum*. These species have developed deep accumulations of peat rising 1–2.5 m above the surface of the terrain, and possessing permafrost below a microbially active layer of 20–30 cm below the living moss surface. The integrity of these moss banks is maintained by the dense rhizoid systems of the two mosses, but particularly by the wicklike tomentum of the *Polytrichum*. The surface of these moss banks is usually colonized by various lichens.

The most diverse and disparate moss-dominated communities are those of fellfields, where environmental conditions fluctuate greatly both diurnally and seasonally. The principal species are mainly those of short cushion and turf growth-forms, with occasional small mats of liverworts. Because of the generally dry nature of the terrain, many lichens coexist with the bryophytes. There is considerable variation in the communities of the maritime Antarctic, usually dominated by species of *Andreaea,* but with numerous associated short acrocarpous species (*Bartramia patens, Bryum* spp., *Ceratodon purpureus, Hymenoloma* spp., *Kaieria pumila, Pohlia nutans, Polytrichum* spp., *Bucklandiella sudetica,* and others). On calcareous, sandstone, and volcanic fellfield soils and gravels, physiognomically similar but floristically different communities occur. These are usually dominated by species of *Schistidium* and *Syntrichia,* with *Bryum* spp., *Ceratodon purpureus, Distichium capillaceum, Ditrichum* spp., *Encalypta* spp., *Hennediella* spp., *Pohlia cruda,* etc. as subordinate associates. Equivalent communities on continental Antarctica are basically similar, but with restricted species composition (e.g., *Bryoerythrophyllum recurvirostre, Bryum* spp., *Ceratodon purpureus, Didymodon brachyphyllus, Hennediella heimii, Sarconeurum glaciale, Schistidium antarctici*).

Peat-Forming Mosses

The dead lower parts of some mosses accumulate to form a type of peat. Only those mosses in wet habitats undergo a significant degree of microbial decomposition and the peat thickness is seldom more than about 10–15 cm thick. However, the moss banks formed by *Chorisodontium aciphyllum* and *Polytrichum strictum* in the northern maritime Antarctic are a unique feature of the landscape. These tall turf-forming mosses grow on relatively dry well-drained hillsides. The rate of organic matter decomposition is very slow and this allows the moss turf to accumulate. Once this peat exceeds about 30 cm depth, permafrost develops and prevents further decay below that level, while the upper living moss layer remains microbially active. This is not a true peat as it has undergone very little loss of mass and the structure of the dead moss turf remains intact. These peat accumulations develop above the surface of the terrain, usually with eroding vertical edges that give the features a distinctive mound shape. In places, the peat thickness is up to 2 m, notably in the South Orkney Islands and a few sites on the midwestern Antarctic Peninsula. They are rare in the South Shetland Islands, yet the deepest known peat deposit formed by these mosses is on Elephant Island, surprisingly at about the altitudinal limit for these phenomena. Radiocarbon dating of peat from the base of the deepest deposits gives ages of 5000–5500 years since the mosses became established.

Mosses in Extreme Habitats

Most habitats in interior continental Antarctica can be regarded as extreme, in terms of low temperature, prolonged drought, rapidly fluctuating thermal and hygric regimes, high and continuous summer solar irradiance, high ultraviolet-B radiation levels, and prolonged winter darkness.

Epilithic (growing on rock) mosses are absent from continental Antarctica, except in the Antarctic Peninsula region. At high elevations and at far southern latitudes mosses occur only as chasmoliths (growing in rock fissures) or on soil adjacent to rock or stones where there is slight moisture retention. In such habitats, they are exposed for long periods to temperatures as low as –40°C to –50°C in winter (no sunlight to warm the substratum, and often only a thin insulating cover of snow) and, more critically, a summer diurnal range of from 15°C–20°C (colony and substratum microclimate) to –30°C. As a probable response to extreme conditions, especially high UV-B levels, most of the few moss species have dark photoprotective pigments.

Only five bryophyte species have been reported beyond 80° S, all in the Transantarctic Mountains, southern Victoria Land *(Bryum pseudotriquetrum, Ceratodon purpureus, Grimmia plagiopodia Sarconeurum glaciale, Schistidium antarctici)*. The farthest south record is of *S. glaciale* Cape Smith (84°42′ S).

Five mosses have been recorded above 1500 m altitude, although two of these occur in the unique habitat provided by geothermal activity near the summits (>2500 m) of the three active volcanoes in Victoria Land (Mt. Erebus, Mt. Melbourne and Mt. Rittmann, see below). The highest known occurrences of mosses in unheated habitats are in several of the mountain ranges in Dronning Maud Land where *Coscinodon lawianus* and *Sarconeurum glaciale* occur at *c*. 2220 m at a site in the Heimefrontfjella. *Bryum argenteum,* has been found at 1540 m on Mt. McGee in Victoria Land.

Active volcanic areas in Antarctica are few, but all possess a unique habitat for bryophyte colonization. The porous ashy soil and scoria, in places directly influenced by geothermal activity and active fumaroles, are kept permanently warm and moist in an otherwise inhospitable environment, thereby permitting some immigrant spores and vegetative structures (propagules) to become established that are unable to do so if they are deposited on unheated substrata. Soil temperatures beneath thermophilic (favouring heated substrates) bryophyte communities are frequently within the range of 25°C–50°C. Three areas in the northern maritime Antarctic possess volcanically heated substrata. These occur between sea level and *c*. 500 m altitude on Bouvetøya (54°25′ S), most of the South Sandwich Islands archipelago (56°–60° S), and Deception Island in the South Shetland Islands (62°57′ S).

In the South Sandwich Islands geothermal habitats occur on Bellingshausen, Candlemas, Leskov, and Visokoi Islands. Around many of the fumarole vents, bryophytes have developed distinct zones, each usually dominated by one to several mosses and liverworts with numerous associated species. Species composition of these zones appears to be dependent on the temperature of the substratum, thereby creating a series of communities along thermal gradients. When ambient air temperatures have been c. 0°C–2°C, temperatures of 50°C within turves of *Campylopus* spp. and *Sanionia uncinata* have been recorded, while at the moss-soil interface (c. 2.5 cm beneath the moss surface), they reached 85°C, rising to over 90°C at 5 cm depth. Those bryophytes most commonly or typically associated with heated ground include the mosses *Bryum dichotomum, Campylopus introflexus, C. spiralis, C. vesticaulis, Dicranella hookeri, Ditrichum gemmiferum, Leptobryum pyriforme,* and *Pohlia nutans,* and several liverworts.

Geothermal areas on Deception Island also possess distinct assemblages of mosses. In less than one year following the 1967 and 1969 eruptions on the island, the cosmopolitan weedy moss *Funaria hygrometrica* was found on steaming ashy soil near the eruption centres. This was its first known occurrence in the Antarctic, although it disappeared within a year or two when the geothermal activity ceased. Distinct but usually sparse communities of mosses occur around fumarole vents, usually dominated by *Dicranella hookeri* and *Philonotis polymorpha.* Steam emissions from fumaroles are about 85°C–95°C, and temperatures within moss turf close to the vents can reach almost 50°C when the air temperature a metre above the ground is around 0°C.

Similar geothermal habitats occur at high altitude near the summits of the volcanoes Mt. Erebus on Ross Island, and Mt. Melbourne and Mt. Rittmann in northern Victoria Land. Here, at altitudes of over 2500 m, ambient conditions are amongst the most severe for life on the planet, yet volcanic activity provides a microenvironment favourable for the development of a very few bryophytes and numerous microalgae. The substratum is maintained continually at temperatures well above freezing, and usually >25°C. With air temperatures permanently below about –20°C, the temperature differential at the soil-air interface creates high humidity, often in the form of steam, which condenses to provide a source of warm liquid water. Steam, often sulphurous or with high levels of CO_2, also emanates from fumarole vents. Although these sites are in total darkness for many months in winter, they either remain snow- and ice-free or are covered by hollow ice-towers up to 3 m high, formed by rime frost crystals, and serving as heated "greenhouses." *Campylopus pyriformis,* a moss typical of geothermally heated soil elsewhere in the world, occurs at c. 3500 m near the summit of Mount Erebus, and at c. 2700 m on Cryptogam Ridge, Mount Melbourne. Temperatures amongst the moss turf ranged from 14°C to 31°C; at 15 cm depth they increased to 40°C–60°C. These are the only sites where *C. pyriformis* has been recorded in continental Antarctica. The moss *Pohlia nutans* occurs at another heated site on Mt. Melbourne, and also on heated compact clay at c. 2600 m below the crater rim of Mt. Rittmann. Temperatures between 25°C and 45°C have been recorded within these populations.

In many continental Antarctic areas several mosses exist in a highly unstable soil environment. They are capable of colonizing loose, porous sandy soils during early summer when they become moistened by melt water sufficiently to afford temporary stability and establishment. The species of such communities (including *Bryoerythrophyllum recurvirostrum, Bryum pseudotriquetrum, B. subrotundifolium, Ceratodon purpureus, Hennediella heimii*) are often buried by water-borne and wind-blown silt and sand to a depth of several centimetres for much of each year. Growth and photosynthesis continue during summer, beneath this protective and insulating mineral layer, as very low levels of light can penetrate the loose crystalline structure of the sand.

Submerged Habitats

A few mosses are restricted to an aquatic environment attached to the bottom sediment of lakes, but some are terrestrial species that have been washed or blown into the water and succeeded in adapting to a submerged lifestyle in the relatively stable thermal conditions. Some of these cover large expanses and achieve shoot lengths of 30–50 cm, far greater than any moss in a terrestrial habitat. The exclusively aquatic species have a remarkable distribution around the continent. *Drepanocladus longifolius* is a wet habitat species of southern South America that occurs in some lakes in the South Orkney and South Shetland islands to 9 m depth. *Plagiothecium orthocarpum* and *Wollnya wilsonii* are terrestrial species, also of southern South America. The former grows to 32 m depth in several lakes in Schirmachar Oasis, Dronning Maud Land, while the latter is found only in a few shallow lakes in Enderby Land where it forms benthic moss "towers" up to 60 cm high. *Bryum pseudotriquetrum,* a terrestrial moss with a global distribution, occurs in several lakes around continental Antarctica and in the maritime Antarctic. Some of these lakes are permanently covered with several metres of ice, including in Lake Vanda in the Dry Valleys of southern Victoria Land, where it grows to a depth of 31 m.

RONALD I. LEWIS-SMITH

See also **Antarctic: Definitions and Boundaries; Antarctic Peninsula; Bouvetøya; Deception Island; Decomposition; Dry Valleys; Lichens; Liverworts; Soils; South Orkney Islands; South Sandwich Islands; South Shetland Islands; Volcanoes**

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MOUNT EREBUS

Mount Erebus (77°32′ S, 167°10′ E; 3794 m) is Antarctica's most active volcano and the southernmost active volcano in the world. It dominates the skyline in McMurdo Sound and is at the center of Ross Island, the home to the United States McMurdo Station and the New Zealand Scott Base. Mount Erebus was discovered in 1841 by British explorer James Clark Ross, who named the volcano after one of his two ships. Ross noted that Erebus was erupting, "... emitting flame and smoke in great profusion...some of the officers believed they could see streams of lava pouring down its sides until lost beneath the snow." Mount Erebus was first climbed in 1908 by members of the British Antarctic *(Nimrod)* Expedition (1907–1909). Erebus is one of the largest volcanoes in the world, ranking among the top thirty in size (1800 cubic kilometers).

It has many unusual features, the most notable being a permanent convecting lake of molten magma with a temperature of 1000°C. The lake was discovered in 1972. By late 2004, this had become two lakes, each about 50 m in diameter. The magma and many older rocks on the slopes of the volcano are rich in sodium and potassium and have phonolite compositions. Early geologists referred to the rocks as kenyte, after Mount Kenya in East Africa, but subtle differences in the mineralogical compositions make this name inappropriate. Large anorthoclase crystals are ubiquitous in the Erebus phonolite and are amongst the largest crystals found in volcanic rocks anywhere on Earth. The crystals can exceed 10 cm in length and they take many different crystal forms. They are easily eroded from the soft glassy matrix of volcanic bombs erupted from the volcano and the crystals litter the upper slopes of the summit crater. During the 1970s, most of the 1980s and 1990s small eruptions were common from the Erebus lava lake and adjacent gas vents, occurring two to ten times daily. The eruptions occasionally throw volcanic bombs onto the crater rim. Since early 2000 eruptive activity has declined. Exceptional Strombolian eruptive activity started on September 14, 1984, and lasted 4 months. Bombs over 10 meters long were erupted and some smaller bombs landed over 3 km from the eruptive vent. More than 100,000 cubic meters of bombs and ash were ejected and some of this partially buried the lava lake. A small research facility just below the crater rim had to be abandoned.

The summit plateau surrounding the active summit crater is dotted with fumarolic ice towers formed when warm volcanic gases (which are mainly water) freeze in the cold ambient air temperatures. Ice caves underlie some ice towers and occur where the warm gases have melted the snow and ice that underlies the ice towers. Small areas of warm ground, some with temperatures of 68°C at 10 centimeters depth, are too hot to sustain ice towers but they do contain thermophilic microbiota and moss.

The most tragic accident in Antarctica's history occurred on November 28, 1979, low on the north slopes of Mount Erebus, when an Air New Zealand DC-10 aircraft on a sightseeing flight crashed, killing all 257 people on board.

Philip R. Kyle

See also **Amundsen-Scott Station; British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); British Antarctic *(Nimrod)* Expedition (1907–1909); McMurdo Station; McMurdo Volcanic Group; Ross Island; Ross, James Clark; Volcanoes**

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MUSIC, ANTARCTIC

There is a limited range of Antarctic music, with very little written by those who have actually been there. The earliest music composed and performed *in situ* was on the British National Antarctic Expedition (1901–1904). "Songs of the *Morning:* A Musical Sketch" was composed on board the relief ship *Morning* by Lieutenant Gerald Doorly and Chief Engineer Morrison. Published in a small edition after the expedition, it has now been recorded.

More serious music had to wait until 1948, when the British classical composer Vaughan Williams composed the music for the film "Scott of the Antarctic." The film score faithfully follows the action of the film and ends in a triumphant outburst after the death of Scott. Later, Vaughan Williams revisited the story and decided to recast the music into a symphony. *Sinfonia Antarctica* (Symphony no. 8, 1952) used many of the original melodies, but the composer decided to end it differently, with a much lower key finale in which the wind howls outside the tent as nature reigns supreme. Vaughan Williams included extracts of Scott's last journal in his score, as well as parts of the Psalms and poetry by Donne, Shelley, and Coleridge. Some performances include these texts, spoken by a narrator.

The British composer Sir Peter Maxwell Davies was at the premiere of *Sinfonia Antartica* in 1953. Nearly 50 years later, he visited the Antarctic at the invitation of the British Antarctic Survey to experience it firsthand, as a condition of his commission to write a sequel to *Sinfonia Antartica. The Antarctic Symphony* was completed in December 2000 and had its broadcast premiere in London on May 6, 2001. The single-movement work offers jagged contrasts—suggesting, for instance, the crashing of icebreaking ships through the frozen sea set against the whisper of snowy avalanches. These contrasts are achieved through a balance of varied tempos and dynamics, with rumbling climaxes of brass and timpani alternating with long-phrased passages, some with shining strings over pizzicato cellos and others featuring a succession of woodwind solos. Sir Peter also fulfilled another commission with Antarctic music. Commissioned to compose for the fortieth anniversary of the National Association of Youth Orchestras, he did so with another "chilling" piece—*High on the Slopes of Terror*—the title coming from a line in the diary of Captain Scott. The score had its premiere in Glasgow on August 31, 2001, with Chethams Symphony Orchestra. Despite performances around the world, it is still not available on CD.

The *Antarctica Suite* by the Australian Nigel Westlake is perhaps more accessible than the music of

Maxwell Davies, being originally composed as film music. Part of the last movement ("The Ice Core/Finale") depicts the scientific study of ice, and the final coda is said to reflect the optimism attending the signing of the Protocol on Environmental Protection to the Antarctic Treaty. One of the strengths of Westlake's piece is the way the guitar, not naturally a *fortissimo* instrument, is balanced against the larger orchestral forces.

The centenary celebrations of the Scottish National Antarctic Expedition in 2004 included some new Scottish music. The Scotia Suite of Scottish Country Dances was devised by Roy Goldring and set to music by Muriel Johnstone. It includes seven dances: "Antarctic Bound," "Scotia Sea," "The Ice Cap," "Coats Land," "Bruce's Men," "The Piper and the Penguin," and "Spiers Bruce—The Pole Star." Music for the dances has been recorded by Neil Barron and his Band, and the accompanying CD also includes pipe music performed by Ian MacInnes and a musical suite "South," performed by the National Youth Orchestra of Scotland.

There are two other forms of Antarctic music—that based on natural sounds and popular music by a wide variety of singers and musicians meant to evoke aspects of the cold continent. Chris Cree Brown is a New Zealand composer whose two works—*Icescape,* for orchestra, and *Under Erebus,* an electroacoustic work—both resulted from a trip to Antarctica in 1999 supported by Antarctica New Zealand, and published by the University of Waikato under the CD title of *the New Zealand Sonic Art Vol II* (MDWU1201).

Music of the environment has been composed by Douglas Quin. His music and soundscape *Australis/Borealis: Sounding Through Light* combines the sound recordings and a chamber ensemble complete with chorus. Similarly, *Antarctica,* by the Canadian folk-singer Ian Tamblyn, uses true-life sounds as integral parts of his tracks, accompanied by piano, guitar, synthesizer, double bass, organ, and a variety of other instruments. His sounds include the wind, Weddell seal pups, Adélie penguins, a variety of birds in flight, the cracking of ice, and the much less natural shuddering and booms of icebreakers and helicopters.

Another piece of music entitled *Antarctica* is an electroacoustic composition realised in 5.1 cinema surround sound by the British percussionist Craig Vear. Vear spent the summer of 2003–2004 in Antarctica as the Arts Council and British Antarctic Survey artist in residence. *Antarctica* is a unique and intriguing combination of a nature documentary, an interwoven experience of wildlife and voices, a radio performance, and a film soundtrack.

Amongst the popular music is that from Koreyoshi Kurahara's film "Antarctica," composed and recorded by Vangelis in 1983. His "Theme from Antarctica" is very floating, symphonic, ethereal, majestic, and emotional, and provides the basis for many of the other tracks on the CD, which are essentially variations on this theme. John Cale composed "Antarctica" for the 1995 film by Manuel Huerga, *Antarctica as a State of Mind.* Valmar Kurol made three visits to the continent before composing, with Marc-Andre Bourbonnais, the CD *Antarctic Arrival*. The compositions are serene, peaceful, and unaffected: much like the frozen south the images convey.

David W. H. Walton

See also **British Antarctic *(Terra Nova)* expedition (1910–1913); British National Antarctic *(Discovery)* Expedition (1901–1904); Scott, Robert Falcon**

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NANSEN, FRIDTJOF

A pioneer Arctic hero, Fridtjof Nansen never went to the Antarctic. However, his influence and inspiration within polar science and exploration made him a major figure in those arenas in the far south. In addition to his status as a polar hero, Nansen was a best-selling author, capable artist, statesman, humanitarian worker, and winner of the Nobel Peace Prize in 1922.

Fridtjof Nansen was born on October 10, 1861, just outside the Norwegian capital Christiania (now Oslo). His father was a lawyer, and his mother came from one of Norway's few aristocratic families (Wedel-Jarlsberg). Nansen took to skiing, including ski jumping, and other sports from an early age and was a pioneer of skiing as a sport. His interest in nature and the outdoors led him to zoology studies at the University of Christiania, and particularly, 4 months on a sealer, *Viking,* in 1882 in order to collect marine specimens in the Arctic. A glimpse of the snow-covered mountains of East Greenland and finds of silt and drift logs in the ice off the coast were both to prove crucial to his later career.

Nansen completed his doctoral thesis in 1888 at the Bergen Museum, writing on the nervous system of lower animals, notably the hagfish. His research was a significant contribution to the subject at that time. By now the idea of crossing the unknown interior of Greenland had taken root and Nansen's daring plan was to ski from east to west, with hope of rescue and a ship home in front of the expedition and not behind. An insistence on science as the prime motive for expeditions was important for Nansen, and was also expressed in his expectations of the younger Roald Amundsen's expeditions. Nansen's attention to detail was revealed in the planning of his Greenland expedition, when he thoroughly tested, invented, and modified equipment, clothing, and food beforehand. Some of his patents, such as a sleeping bag, Nansen sledge, cooking apparatus, and layered clothing, became prototypes for later expeditions in the Arctic and Antarctic.

Nansen took five others with him across Greenland in 1888, including two Sami from northern Norway whom he thought would be excellently adjusted to such an expedition. This proved to be not quite true, but instead Nansen used the winter spent in Godthåb (Nuuk) after the crossing to study thoroughly the Greenlanders' adaptations to a harsh polar climate. The notion of learning from polar people was picked up by Amundsen, who used techniques learned from the Inuit on his successful South Pole expedition.

Nansen was feted as a hero on his return to Christiania in 1889 with his position as a polar authority and expedition hero now established. He married the singer Eva Sars and was appointed conservator at Christiania University. The theory of an east–west drift across the Arctic Ocean now intrigued him. Meteorology professor Henrik Mohn had first voiced this on the basis of artefacts from the US ship *Jeannette* found off southwest Greenland in 1884. *Jeannette* had been crushed in the ice north of the New Siberian Islands in 1881. Nansen's finds of silt and drift logs off the East Greenland coast were further indications.

Against the advice of many international polar authorities of the time, Nansen devised the plan of drifting with the presumed current in a specially designed ship that would withstand the force of the pack ice.

The drift in the ship *Fram* east to west across the Arctic Ocean in 1893–1896 was a great success and yielded a huge amount of scientific data as well as increasing Nansen's polar expertise and reputation. He was now indisputably the polar expert of the time, not least for his ability to understand and formulate scientific challenges in the polar areas. Having discovered that the Arctic is a deep ocean surrounded by land, and understanding that the Antarctic on the other hand appeared to be land surrounded by sea, his next wish was to attempt to reach the South Pole to investigate the unknown continent. He already had *Fram* available to get him down south. However, Nansen's worth for Norway, struggling to leave the union with Sweden and establish itself as an independent nation, was too great for him to be able to disappear into the polar wastes again. He became fully engaged in political and diplomatic missions, assisting in bringing a new royal family to Norway in 1905 and becoming Norway's first envoy to London 1906–1908.

The decision of the Sixth International Geographical Congress in London in 1895 to encourage Antarctic research was given impetus by Nansen's Arctic Ocean discoveries, and the way was opened for the Heroic Era in Antarctic exploration to begin.

In 1907 Roald Amundsen approached Nansen to ask for advice concerning his plans to repeat the drift across the Arctic Ocean, but this time to reach the North Pole. Nansen recommended *Fram* as the only suitable ship, but stated that he himself would be using it for a South Pole expedition. When he finally conceded that this was not to be, Amundsen was allowed to take it on his expedition that actually went to the South Pole (1910–1912). Amundsen was asked to take Nansen's experienced companion from the *Fram* expedition, Hjalmar Johansen, with him. Because of their support, Nansen and King Haakon of Norway were the two persons that Amundsen most feared when he announced his change of plans, to go to the South Pole instead of the North Pole. Nansen was disappointed by this change, but defended Amundsen in public.

Nansen's advice was sought by many others with interest in or plans for polar work and expeditions. Ernest Shackleton talked with him in London in 1907, and asked Nansen to see the expedition off. Robert Falcon Scott met Nansen in Norway in March 1910 to test equipment, and was advised to use dogs. Nansen suggested that Scott take the young Tryggve Gran with him to the Antarctic as a ski expert.

After World War I, Nansen turned to humanitarian work with the League of Nations, working particularly with Russian refugees and the Soviet famine crisis. For this he received the Nobel Peace Prize. Nansen was a prolific writer and speechmaker. He died at his home outside Oslo in 1930.

SUSAN BARR

See also **Amundsen, Roald; Scott, Robert Falcon; Shackleton, Ernest**

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NATIONAL ANTARCTIC RESEARCH PROGRAMS

This entry describes, in alphabetical order, the national Antarctic research programs of those countries whose programs do not have a separate entry.

Czech Republic

Czechoslovakia acceded to the Antarctic Treaty on 14 June 1962. The Czech Republic and the Slovak Republic have maintained their accessions individually since they separated on 1 January 1993. The Czech Republic is expected to become an Associate Member of the Scientific Committee on Antarctic Research (SCAR) in 2006.

Czech scientists were active in Antarctic research during the 1950s and 1960s, mainly in the fields of astrophysics, geophysics, meteorology, and geology, working with the scientific programmes of other nations. A renewal of research activity in the 1990s gave rise to a determination to establish a Czech station in Antarctica to carry out research independently. Czech scientists visited Antarctica in several seasons to prospect for a site that would be appropriate for continuing their current scientific interests, including terrestrial biology.

In February 2005, construction of the Mendel station began at a site on the northern shore of Ulu

Peninsula (63°48′ S, 57°53′ W), between Bibby Point and Cape Lachman at the northern end of James Ross Island, northeastern Antarctic Peninsula, and several buildings were erected before the end of the season. The building work was completed in the 2005–2006 season. Research programmes are planned in the following fields: geology, geomorphology, climatology, terrestrial ecosystems, and freshwater ecosystems.

Ecuador

Ecuador acceded to the Antarctic Treaty on 15 September 1987, became an Associate Member of SCAR on 12 September 1988, became a Consultative Party of the Antarctic Treaty on 19 November 1990, and became a Full Member of SCAR on 15 June 1992.

The Ecuadorian navy operates the RV *Orion* for marine research and the support of the summer-only station Vicente (62°8′ S, 58°22′ W) close to Point Hennequin on the eastern shore of Admiralty Bay, King George Island, South Shetland Islands.

Estonia

Estonia became an Associate Member of SCAR on 15 June 1992, but withdrew from SCAR on 22 August 2001. Estonia acceded to the Antarctic Treaty on 17 May 2001.

Estonian scientists were active in Antarctic research for many years within the program of the Soviet Union. Some of these have continued their research in the 1990s by working with other national programs.

Estonia is planning to erect a small summer-only station in the general vicinity of Terra Nova Bay, Victoria Land, from which a limited program of research will be conducted.

Malaysia

Malaysia became an Associate Member of SCAR on 4 October 2004 and is expected to accede to the Antarctic Treaty in 2006.

Malaysian scientists have been active in Antarctic research for several years, working within other national programs, particularly those of Argentina, Australia, and New Zealand. The main field of interest has been in meteorology and other aspects of atmospheric sciences, but this will expand into biological sciences, including the biodiversity of benthic invertebrates, microbial studies, and genetic studies. Currently, there are no plans to build a station.

Pakistan

Pakistan became an Associate Member of SCAR on 15 June 1992 but has not acceded to the Antarctic Treaty.

Pakistan despatched an expedition to Greater Antarctica in January 1991 under the auspices of the National Institute of Oceanography. A few small buildings were erected, on stilts, on the surface and partially dug into the snow to determine the drift characteristics of each structure. These constituted Jinnah Antarctic Research Station, located at 70°25′ S, 25°46′ E on the Prinsesse Ragnhild Kyst of Dronning Maud Land. In addition to research facilities, the station houses a sophisticated unmanned Automatic Weather Station from which weather data are transmitted to Pakistan via the Argos satellite system. The station was revamped during the second Pakistan expedition to Antarctica during the 1992–1993 austral season. There have been no reports of further activities.

Peru

Peru acceded to the Antarctic Treaty on 10 April 1981, became an Associate Member of SCAR 14 April 1987, became a Consultative Party to the Antarctic Treaty on 9 October 1989, and became a Full Member of SCAR on 22 July 2004.

The Antarctic Program of Scientific and Technological Research (PROANTARCYT) of Peru in Antarctica works in close cooperation with the Scientific Subcommission of CONAAN, comprising Peruvian universities and the National Research Institutes.

Peru established a small summer-only station, Machu Picchu (62°05′ S, 58°28′ W), near the head of Admiralty Bay, King George Island, South Shetland Islands. The station opened in February 1989 and can accommodate a maximum of twenty-eight personnel. The principal scientific activities include environmental monitoring, geomagnetic observations, human biology, meteorology, offshore marine biology, onshore geology/geophysics, stratospheric ozone monitoring, terrestrial biology, and tidal measurements.

Marine science and station resupply are carried out by the research vessel *Humbolt*.

Sweden

Sweden acceded to the Antarctic Treaty on 24 April 1984, became an Associate Member of SCAR on 24 March 1987, became a Full Member of SCAR on 12 September 1988, and became a Consultative Party to the Antarctic Treaty on 21 September 1988.

The Swedish debut in Antarctica was the Swedish South Polar Expedition (1901–1903) of Otto Nordenskjöld, which established a base on Snow Hill Island, off the northeastern tip of the Antarctic Peninsula, and explored in that general area.

In the 1987–1988 summer season, Svenska Antarktisforskningsprogrammet (SWEDARP) (Swedish Antarctic Research Programme) personnel, transported aboard the German vessel *Polarstern,* established a field station, Svea (74°35′ S, 11°13′ W), in Heimefrontfjella, Dronning Maud Land, to undertake glaciological, survey, and geological studies. In the 1988–1989 summer season, a new larger station, Wasa (73°03′ S, 13°25′ W), was established in Vestfjella, Dronning Maud Land, adjacent to the Finnish station Aboa. Since this time the Nordic Antarctic operators—Finland, Norway, and Sweden—have taken annual turns to provide logistic support for scientists of all three countries to work in Dronning Maud Land. Swedish scientists also are active in other Antarctic areas, working in collaboration with the other national programs.

Swedish Antarctic research priorities include deep water formation and interaction among sea, ice, and air in the Weddell Sea; atmospheric composition and processes; marine ecosystems related to global change and commercial use; mass balance of ice sheets and glaciers, related to climate change and sea-level fluctuations; participation in international deep drilling/ice coring programmes, for reconstruction of past climate and atmosphere composition, and for using the ice sheet as a detector medium in astrophysics; geological and tectonic development; and satellite techniques for remote sensing of ice sheets and for geodetic purposes.

Switzerland

Switzerland became an Associate Member of SCAR on 16 June 1987, acceded to the Antarctic Treaty on 15 November 1990, and became a Full Member of SCAR on 4 October 2004.

Swiss scientists have been active in Antarctic research since 1968, particularly in the field of glaciology, working with scientists in other national programs, notably those of the United States, Italy, and New Zealand. The analysis of deep ice cores from Antarctica, most recently in the programme of European Polar Ice Coring in Antarctica (EPICA), has been a major focus in glaciology, but fieldwork has also been conducted in glacial geology. There are currently no plans to build a station in Antarctica.

Uruguay

Uruguay acceded to the Antarctic Treaty on 11 January 1980, and became a Consultative Party on 7 October 1985. Uruguay became an Associate Member of SCAR on 29 July 1987, and a Full Member on 12 September 1988.

The initial involvement of Uruguay with the Antarctic was in April 1916 with the despatch of the *Instituto de Pesca No. 1* in the second unsuccessful attempt to rescue the men of Sir Ernest Shackleton's Imperial Trans-Antarctic Expedition, who were stranded on Elephant Island in the South Shetland Islands.

In January 1984 a reconnaissance visit was made to King George Island, South Shetland Islands, to search for a suitable site for a scientific station. In December 1984 Artigas station (62°11′ S, 58°57′ W) was established on Fildes Peninsula, King George Island. On 8 December 1997, the hut of the former British Base D at Hope Bay, northeast-most Antarctic Peninsula, was transferred to Uruguay and refurbished as a summer-only station, Ruperto Elichiribehety (63°24′ S, 56°54′ W). The navy vessel *Vanguardia* provides logistic support and station resupply and acts as a platform for marine science.

Research activities include ornithology, geodesy, tidal studies, meteorology, glaciology, psychological and medical studies, and ozone measurements.

PETER CLARKSON

See also **Antarctic: Definitions and Boundaries; Antarctic Peninsula; Antarctic Treaty System; Argentina: Antarctic Program; Australia: Antarctic Program; Finland: Antarctic Program; Germany: Antarctic Program; Imperial Trans-Antarctic Expedition (1914–1917); Italy: Antarctic Program; King George Island; New Zealand: Antarctic Program; Nordenskjöld, Otto; Norway: Antarctic Program; Scientific Committee on Antarctic Research (SCAR); Shackleton, Ernest; Swedish South Polar Expedition (1901–1904); Swedish South Polar Expedition, Relief Expeditions; United States: Antarctic Program**

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NATIONAL INSTITUTE OF POLAR RESEARCH, JAPAN

The National Institute of Polar Research (NIPR) has its head office complex in Tokyo. Three buildings with a total floor area of 11,177 m^2 occupy 5945 m^2 of land area. The complex contains various facilities, such as offices, wet and dry laboratories, a computer room, and a library.

The "Polar Department" was established in April 1962 in the National Science Museum, Tokyo, to promote the Japanese Antarctic Research Expedition (JARE). The Department was enlarged in several steps. NIPR in its present form was established on September 29, 1973 as one of the Inter-University Research Institutes of the Monbusho (Ministry of Education, Science, Sports, and Culture). In April 2004, NIPR was detached from the government and became a public corporation, sponsored by the former Monbusho, which had also changed its own structure and become the Monbu-Kagakusho (Ministry of Education, Culture, Sports, Science, and Technology, or MEXT).

NIPR's annual budget was 3951 million yen in fiscal year 2003. (All the figures hereafter refer to those of 2003.) One hundred forty-nine personnel were employed in the year, under the Director-General, Prof. Okitsugu Watanabe: sixty-nine researchers, fourteen engineers, twenty-nine administrators, and thirty-seven expedition members. (Researchers included five visiting professors, seven visiting associate professors, and an adjunct research fellow.)

The function of the NIPR was assigned at the time of the establishment of the institute in 1973, and is still effective: it shall conduct polar research for Japan. The task takes various forms.

1. Research activities of the permanent staff cover a wide range of scientific disciplines, including upper atmosphere physics, meteorology, glaciology, earth sciences, biological sciences, and polar region engineering.
2. NIPR is in charge of implementing the scientific and logistics programs of the Japanese Antarctic Research Expedition, which is under the authority of JARE Headquarters, chaired by the minister of MEXT. NIPR is responsible for maintaining four Antarctic stations: Syowa Kiti (Syowa Station) on East Ongul Island; and Mizuho Kiti (Mizuho Station), Asuka Kiti (Asuka Station), and Dome Fuji Kiti (Dome Fuji Station) on the mainland.
3. NIPR carries out many national and international cooperative projects with research organizations outside the institute. Currently 500 Japanese investigators are affiliated with NIPR.
4. NIPR provides postgraduate students with the opportunity to conduct their doctoral thesis research using relevant Antarctic data and analytical facilities.
5. NIPR is responsible for collecting, processing, and utilizing data and samples obtained by Antarctic and Arctic investigations. Data and specimens in the fields of biology, glaciology, and aurora physics are dealt with at the Division of Polar Information of the institute. These data and specimens are used for joint research programs with other institutions at NIPR, or are distributed to qualified scientists based on advice from advisory committees such as the Antarctic Meteorite Research Committee and Ice Core Research Committee. Aurora data are preserved at the World Data Center for Aurora. The Computing and Communication Center is equipped with powerful data-processing facilities, a Multipurpose Satellite Data Receiving System, and a polar information retrieval system. The Arctic Environment Research Center operates an Arctic field laboratory in Ny-Alesund, Svalbard. The Polar Research Resources Center studies the Antarctic environmental system in conjunction with the global system. NIPR established an Antarctic Meteorite Research Center in 1998. The library is responsible for collecting literature relevant to polar research. It also publishes about 3000 pages of scientific papers annually.
6. Permanent members of NIPR represent various national and international polar research organizations. NIPR established and continues to operate national Antarctic data centers for aurora, biology, glaciology, solid earth geophysics, geology, upper atmosphere physics, and logistics in cooperation with Working Groups of SCAR of the International Council of Scientific Unions.

7. NIPR invites visiting professors and provides research fellowships for visiting investigators from abroad. In addition, each year NIPR invites several scientists from abroad to participate in its annual symposia.

Antarctic and Arctic Stations

Four scientific stations (Syowa, Mizuho, Asuka, and Dome Fuji) in the Antarctic and a station in Ny-Alesund in the Arctic are affiliated facilities of NIPR and are maintained and managed by NIPR.

Syowa Station was established by Japan's First Antarctic Expedition, on January 29, 1957, near the eastern shore of Lützow-Holm Bay, East Antarctica. The station is located on Ongul Island, about 4 km west of the edge of continental Antarctica. The station is a straight-line distance of approximately 14,000 km from Tokyo. Its coordinates are 69°00′ S and 39°35′ E, and it is 29 m in elevation. The base is built directly on bedrock, and consists of an administration building, an electric power plant, living quarters, observation and research buildings, environmental protection facilities, satellite telecommunications buildings, and warehouse facilities, with a total floor area of 6100 m^2. Approximately forty people winter at the base each year to conduct research and observational activities.

Dome Fuji Station was established on January 29, 1995 by the 35th and 36th Antarctic Expeditions. It is located approximately 1000 km south of Syowa Station at the highest point on the Dronning Maud Land ice sheet. The station is situated at 77°19′ S and 39°42′ E at an elevation of 3810 m. The station consists of an electric power plant, dining hall, residential facilities, laboratory, combined medical and residential building, drilling workroom, excavation control room, passageways, and evacuation facilities, all with a combined floor area of 386 m^2. Additionally, the station has a 4-m-deep by 22-m-long trench for deep layer excavation, an ice-core processing and experimentation facility, and other facilities that are dug into the snow. It was here at Dome Fuji Station that the 36th Expedition wintered over and excavated the ice sheet to a depth of 2500 m. Core samples thus obtained enabled researchers to study 340,000 years of global climate and environmental change. The expedition also conducted monitoring in the study of atmospheric and material circulation systems, the chemical properties of snow accumulation, and the dynamics of ice-sheet movement.

Dome Fuji Station is located at high altitude, and its weather is characterized by extremely low temperatures and light winds.

Weather Statistics at Syowa Station

Average temperature	–10.5°C
Recorded maximum temperature	10.0°C (January 21, 1977)
Recorded minimum temperature	–45.3°C (September 4, 1982)
Average wind speed	6.5 m/s
Recorded maximum instantaneous wind speed	61.2 m/s (May 27, 1996)
Average sea-level air pressure	986.6 hPa
Average relative humidity	66%

Weather Statistics at Dome Fuji Station

Average temperature	–54.3°C
Recorded maximum temperature	–18.6°C
Recorded minimum temperature	–79.7°C
Average wind speed	5.8 m/s
Average sea-level air pressure	598.4 hPa

OKITSUGU WATANABE

See also **Antarctic: Definitions and Boundaries; Japan: Antarctic Program; Scientific Committee on Antarctic Research (SCAR)**

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NIPR has many publications:
1. Five journals in English: *Advances in Polar Upper Atmosphere Research; Polar Meteorology and Glaciology; Polar Geoscience; Antarctic Meteorite Research;* and *Polar Bioscience*.
2. *Antarctic Record* (*Nankyoku Shiryo* in Japanese), comprising English and Japanese papers and reports in three volumes annually.
3. *JARE Data Reports* in ten fields in English.
4. *Memoirs of National Institute of Polar Research,* an occasional publication in six fields in English.
5. *Antarctic Geological Map Series*.

Japanese Antarctic Research Expeditions. http://www.nipr.ac.jp/english/ara01.html

National Institute of Polar Research. http://www.nipr.ac.jp/

NEMATODES

Nematodes (phylum Nematoda) are unsegmented, vermiform animals with adults ranging in length from 0.3 mm to over 8 m. Nematodes are the most abundant multicellular animals on earth, and their distribution and abundance in Antarctica reflects the same physical, chemical, and biological factors that affect their populations elsewhere. To feed, grow, and reproduce they require free water. Nematodes inhabiting soils and aquatic sediments typically feed on microbes, plants, or other microfauna, and populations may reach millions m^{-2}, containing over 200 species. Their feeding activity enhances nutrient cycling and other ecosystem processes. Nematodes living in plants, invertebrates, and vertebrates may affect host condition, particularly when infestations are great or the host is stressed. The juvenile stages of these "parasites" may develop in inert sediments, invertebrates, or vertebrates.

Air, water, and animal movement aid nematode dispersal. But colonisation of habitats, the establishment of ongoing populations, requires nematodes to survive local conditions—in continental Antarctica they face dual stresses of low temperature and desiccation. Terrestrial nematodes survive freezing and desiccation in a dormant state but grow and reproduce when conditions are favourable. In *Panagrolaimus davidi* (order Rhabditida), the sugar trehalose and ice-active proteins may inhibit crystallisation that would otherwise cause cell damage and death on rapid freezing; under slow freezing it shows dehydration and anhydrobiosis, perhaps accompanied by trehalose synthesis. *Ditylenchus parcevivens* (order Tylenchida) and *Teratocephalus tilbrooki* (order Chromadorida) are, in contrast, fast dehydration strategists. The adaptations required to meet these conditions increasingly restrict the diversity of terrestrial nematodes at higher latitudes; more than twenty-five nematode species are known from Signy Island, approximately five on Ross Island and the Dry Valleys of Victoria Land, and only a single species on Steinnabben nunatak in East Antarctica.

In their coastal colonies, penguins, through excreta, moulting, and death, transfer nutrients from marine to terrestrial environments. Thus, at least during the summer, colonies are the scene of significant biological activity because nematodes, along with microfauna such as tardigrades and rotifers, use this resource and the microbes associated with it. Four soil nematode species occur near Ross Island penguin colonies, but only *Panagrolaimus davidi* has been collected within colonies, and high salinity is thought to exclude the other bacterial-feeding nematodes (*Plectus antarcticus,* Plectidae; *Scottnema lindsayae,* Rhabditida) and omnivorous nematodes (*Eudorylaimus antarcticus,* Dorylaimida) found in the vicinity. Apparently the adaptations that enable *P. davidi* to survive freezing and desiccation also confer resistance to severe osmotic stress.

The nematodes known from the vicinity of Adélie penguin colonies are those that occur in the Dry Valleys of Victoria Land, where diffuse aerial input of organic matter supports simple terrestrial food webs. Habitat patches supporting *S. lindsayae* over several years seem least suitable for *P. antarcticus* and *E. antarcticus,* suggesting that variation in soil conditions (e.g., moisture, pH, salinity, ratio of carbon to nitrogen) on the scale of tens of metres, rather than dispersal, controls the distribution of these nematodes. This suggests that both idiosyncratic variation in snowdrifts and climate change may significantly impact these populations. Knowledge of factors influencing these distributions will prove useful in understanding the spatial heterogeneity of nematode populations in more complex ecosystems.

At least twenty-five nematode species, together with rotifers and tardigrades, have been collected from nunataks, with *Eudorylaimus nudicaudatus* (Dorylaimida) and *Chiloplacoides antarcticus* (Rhabditida) being known only from such sites. However, only four species have actively growing populations and are clearly established. On nunataks, the largest nematode populations, including *Panagrolaimus* sp., are found in association with colonies of snow petrels *(Pagodroma nivea),* and generally more nematodes are recovered from samples with moss, blue-green alga *(Nostoc),* or green alga *(Prasiola)* than from material with lower organic matter content. Collection of individual or small numbers of nematodes from such localities may indicate that they have dispersed but have not colonised; records from continental Antarctica of nematodes such as *Helicotylenchus, Tylenchorhynchus,* and *Rotylenchus* (Tylenchida) that feed on higher plants probably belong in this category.

Nematode assemblages in soils around mosses and vascular plants in the maritime Antarctic (e.g., Signy Island) are functionally and taxonomically comparable with those of nearby more temperate sites. In maritime Antarctica, nematode-trapping fungi (e.g., *Arthrobotrys, Monacrosporium, Harposporium*) are widespread; related forms have been found in continental Antarctica (Ablation Point, Alexander Island; Victoria Land).

Lake systems in East Antarctica have yielded five nematode species, with many lakes having only one species. Nematodes have long been known to be abundant and diverse in Antarctic marine sediments, and at 200- to 2000-m depth on the Weddell Sea shelf their diversity may surpass that of the Arctic bathyal assemblage. As for the Arctic, some marine nematodes (e.g., *Geomonhystera*) are found in sea ice, and marine invertebrates (e.g., *Diplopteraster perigrinator,* Echinodermata; *Eulagisca gigantea,* Polychaeta) may be parasitised by nematodes.

Among nematode parasites of vertebrates, adults of *Pseudoterranova decipiens* (Ascaridida, Anisakidae) have the Weddell seal *(Leptonychotes weddelli)* and the elephant seal *(Mirounga leonina)* as the main final hosts, being found in the stomach. Third-stage juveniles of *P. decipiens* occur predominantly in fish that feed on benthic nototheniid fishes; pelagic or euphausid feeding fish species are less infected, indicating a benthic life cycle. Earlier developmental stages infect crustaceans. Adults of other nematode species occur in the stomach and intestine (e.g., *Anisakis physeteris* with euphausids and fish as intermediate hosts) or urinogenital system (e.g., *Crassicauda crassicauda, Placentonema gigantissima*) (Spirurida, Tetrameridae) of various whale species.

As in the rest of the world, nematodes are abundant and diverse in the Antarctic. They show a range of adaptations to permit their dispersal, survival, and the utilisation of a range of terrestrial and marine food resources, as well as parasitising invertebrates and vertebrates.

G. W. Yeates

See also **Adélie Penguin; Algae; Dry Valleys; Elephant Seal; Mosses; Ross Island; Rotifers; Tardigrades; Weddell Seal**

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NEOTECTONICS

Neotectonics (active or recent tectonics) is a broad field of study examining geologically recent movements of the Earth's surface. Earthquakes (seismicity) and fault slip, volcanic activity, and the response of the solid Earth to the fluctuations of ice sheets and glaciers (glacial isostasy) contribute to neotectonic activity in Antarctica. Antarctica is unique—it is nearly completely covered by ice (98%) and almost entirely surrounded by oceanic spreading ridges—and this gives rise to exceptional neotectonic activity. This focus is on active tectonics.

The detection and location of earthquakes in Antarctica has been hampered by the limited number of seismometers, most of which are located on the periphery of the continent. Until recently, no earthquakes had been observed for large interior regions. This led to the suggestion that these regions might be aseismic—that is, that they experience no earthquakes at all. This was ruled out only recently, when small earthquakes were detected by temporary networks of seismographs in the continental interior. Nevertheless, even with the newly observed earthquakes, Antarctica has a low level of seismicity.

Unlike most continents, which have zones of tectonic convergence (compression) where mountains are built and earthquake activity is frequent, Antarctica is almost completely surrounded by oceanic spreading ridges. This may put the continent in a relatively low state of stress and could explain the limited occurrence of earthquakes. As well, the weight of the ice sheets and glaciers squeezes and compresses the underlying bedrock, and this is thought to suppress earthquakes. The largest observed earthquake had a magnitude of less than 5, which is small compared to the earthquakes with magnitudes of 6 and 7 observed in other intraplate continental settings.

The Transantarctic Mountains (TAM) are a major structural feature separating East and West Antarctica. Their formation is linked to the Cenozoic rifting that formed the West Antarctic Rift System (WARS), a major geological structure. The TAM contain some of the oldest surfaces on Earth, aged many millions of years, yet surface uplift may be presently occurring at a low rate due to basal erosion by cross-cutting outlet glaciers originating in East Antarctica.

Much of the sparse continental seismicity occurs along the TAM and adjacent WARS. Crustal extension of a few millimeters per year has been observed in some parts of the TAM by Global Positioning System (GPS) measurements. Field observations indicate possible recent slip on faults. The crustal extension could be tectonic, could originate in the Earth's response to ice-sheet changes, or could be a combination of the two.

Tectonically mobile West Antarctica also features a mantle plume centered beneath Marie Byrd Land, which is thought to be responsible for crustal doming and volcanism. Active volcanoes in Antarctica, such as Mount Erebus, generate local crustal deformation and small earthquakes, or tremors. In contrast to West Antarctica, East Antarctica is considered to be a stable cratonic region, although recent observations suggest low levels of crustal deformation in some localities.

Regions with active tectonics frequently exhibit high geothermal heat flow. Low heat flow promotes a frozen glacier bed, while high heat flow promotes basal sliding and faster glacial flow. Subglacial lakes are unique environments that are sensitive to heat received from the underlying crust. The habitat of the largest of these, Lake Vostok, may be influenced by its location on a seismically active geological structure.

The ice sheets and glaciers that cover nearly all of Antarctica have fluctuated in their extent and thickness and are presently changing in size. The changing weight of the ice drives a complex pattern of crustal uplift and subsidence known as glacio-isostatic adjustment that is still poorly discerned. Unlike the Northern Hemisphere, where the history of crustal uplift and subsidence after deglaciation is preserved in numerous raised beach deposits, relatively few observations are available for Antarctica because most shorelines are covered by ice. The limited available observations show that sea level has generally not fluctuated by more than about twenty meters in the past 5000–6000 years. Modern space-based geodesy, including satellite gravity missions and GPS, is increasingly being used in Antarctica to determine the earth's present-day response to tectonic forces and changes in ice mass.

Thomas James

See also **Antarctic: Definitions and Boundaries; Antarctic Ice Sheet: Definitions and Description; East Antarctic Shield; Geological Evolution and Structure of Antarctica; Ice Ages; Lake Vostok; Mount Erebus; Plate Tectonics; Remote Sensing; Subglacial Lakes; Transantarctic Mountains, Geology of; Volcanoes; West Antarctic Rift System**

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NETHERLANDS: ANTARCTIC PROGRAM

The Netherlands Polar Programme (NPP) has existed since 2002. It is a merger of the Netherlands Antarctic Programme (NAAP, in existence since 1985) and a conglomerate of Arctic projects financed and administered through NWO (Netherlands Organization for Scientific Research). The funding for polar research in the Netherlands comes from five ministries: (1) Foreign Affairs, (2) Housing, Spatial Planning, and Environment, (3) Transport, Public Works, and Water Management, (4) Agriculture, Nature, and Food Quality, and (5) Education, Culture, and Science. The department of Foreign Affairs chairs this Interministerial Polar Committee and deals with Antarctic Treaty matters.

Polar research proposals are judged on five policy criteria in order to be funded: (1) scientific quality, (2) political and social relevance, (3) international links, (4) relation to the research themes of the Netherlands Polar Programme (Glaciology and Climatology; Marine Sciences; Ecology; Man and the Polar Environment), and (5) the urgency and especially the feasibility of the proposal.

Any member of the research community can submit proposals for Antarctic research, but they are generally associated with one of the four leading research institutes in this field: the Institute for Marine and Atmospheric Research (IMAU, of the University of Utrecht), the Royal Netherlands Institute for Sea Research (RoyalNIOZ), the Netherlands Institute of Ecology (NIOO-KNAW), and the Arctic Centre (of the University of Groningen). These four institutes are regularly consulted as to what the research themes of the country's polar programme should be. The proposals for research are submitted to the Committee on Polar Research (part of NWO), which evaluates and prioritizes them via an international panel of referees. The proposals then go to the Interministerial Polar Committee. This committee makes the final assessment of the proposals and hands out funding.

The current budgets per annum are €140,000 for Arctic research and €2.7 million for Antarctic research. This money is divided fairly evenly between logistics and research.

The Netherlands has no Antarctic infrastructure of its own—that is, no ship, no research station, no aircraft. It does, however, have memorandums of understanding (MOUs) with several international organizations, such as the British Antarctic Survey and Germany's Alfred Wegener Institute. A yearly amount is paid to the international partner to use their logistical facilities, regardless of how many Dutch scientists go to Antarctica in a given year. The MOUs stipulate that the Dutch projects should be in collaboration with those of the host country. Advantages of this type of system include that the Netherlands spends less on logistics (40%–50% versus 80% by some other countries) and that research is not restricted to a single location.

AD H. L. HUISKES

See also **Alfred Wegener Institute for Polar and Marine Research, Germany; British Antarctic Survey**

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Netherlands Polar Program. http://www.nwo.nl/npp

NEUMAYER, GEORG VON

Georg Balthasar von Neumayer was born on June 21, 1826, at Kirchheimbolanden, and died on May 24, 1909, at Neustadt/Pfalz.

In 1849, Neumayer finished his studies at the Engineering School and Polytechnical School (today Technical University) at Munich. He then became the assistant to Johann von Lamont (1805–1879), director of the observatory at Bogenhausen/Munich and leading authority in terrestrial magnetism. Within several months Neumayer was introduced to meteorological and magnetic measurements.

When he was not accepted to join the navy in 1850, Neumayer bought a berth on a barque from Hamburg to South America to gain practical experience in seamanship and navigation. After his return to Hamburg he passed his mate's certificate under the director of the observatory and school of navigation, Carl Christian Ludwig Rümker (1788–1862) in May 1851. He then went to Triest, where he tried in vain to join the newly established Austrian Navy.

Back in Hamburg, Neumayer lectured some months at Rümker's school, introducing Matthew Fontaine Maury's (1806–1873) new hydrographical method of preparing sailing directions from the analysis of winds and currents recorded in special ship logs. In 1852, Neumayer sailed to Australia, serving before the mast. He came back to Germany in 1854 with the plan to establish a geophysical observatory at Melbourne that could serve as a base for a later expedition to Antarctica. Following Lamont's advice, Neumayer first gained practical experience during extended magnetic surveys in Germany. When the Bavarian king granted financial support to buy the newest instruments, he founded the Flagstaff Observatory at Melbourne in 1857, directing it until 1864.

After his return to Germany, Neumayer plead in vain for a German Antarctic expedition during the first meeting of German geographers at Frankfurt/Main in 1865. He ultimately was named leader of an Austrian Antarctic expedition, which could not be realized due to the death of its major supporter, Admiral Wilhelm von Tegetthoff (1827–1871).

After the foundation of the German Reich, Neumayer moved to Berlin to become hydrographer of the Admiralty (1872–1875). He was in charge of the scientific program of the *Gazelle* expedition (1874–1876), during which the transit of Venus was observed at Îles Kerguelen in the Southern Indian Ocean in 1874. From 1875 until 1903 he directed the newly established Deutsche Seewarte (Naval Observatory) at Hamburg. In this position he influenced nautical and geophysical techniques of measurement and used his talent as an organizer of scientific research.

Neumayer was a key figure in the realization of the first International Polar Year (1882–1883). One of the consequences of that international program was the foundation of the German Meteorological Society in 1883, over which Neumayer presided until 1888. He continued to emphasize the advantages that could accrue through international cooperation in Antarctica, and much of the joint international program conducted in the period from 1901–1904 was organized following his concepts. He was the guiding force during the preparations for the first German Antarctic expedition (1901–1903), playing a similar role to Clements Markham's in Great Britain. In 1900, Neumayer was raised to the Bavarian nobility.

CORNELIA LÜDECKE

See also **Drygalski, Erich von; German South Polar *(Gauss)* Expedition (1901–1903); International Polar Years; Markham, Clements**

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NEW ZEALAND: ANTARCTIC PROGRAM

On July 30, 1923, Britain claimed the Ross Dependency, and placed it in the care of New Zealand. The dependency lies between 150° W and 160° E, and includes Ross Island, the site of New Zealand's Scott Base, built in 1957 to support the Commonwealth Trans-Antarctic Expedition (CTAE) and the International Geophysical Year (IGY) scientists. Successful international cooperation in the IGY led to the signing of the Antarctic Treaty, with New Zealand an original signatory.

Scott Base became a permanent base in 1959–1960 and was managed by the New Zealand Antarctic Programme (NZAP) under the auspices of the Department of Scientific and Industrial Research (DSIR). In 1992, NZAP became the responsibility of the Ministry of Foreign Affairs and Trade (MFAT). In 1994, there was a further review of New Zealand's involvement in Antarctica, resulting in the establishment of Antarctica New Zealand.

Based in Christchurch, Antarctica New Zealand is a Crown Entity, established under the *New Zealand Antarctic Institute Act 1996*. It has a board appointed by the Minister of Foreign Affairs and Trade, twenty-six staff in Christchurch, and an annual summer staff of twenty to thirty at Scott Base, with ten wintering over in Antarctica each year. Through Scott Base, access, services, and accommodation are provided to all people who travel to Antarctica under the New Zealand Antarctic programme.

Antarctica New Zealand's key functions are as follows:

- Develop, manage, and execute New Zealand activities with respect to Antarctica and the Southern Ocean.
- Maintain and enhance the quality of New Zealand Antarctic scientific research.
- Cooperate with other institutions and organisations, both within and outside New Zealand, that have objectives similar to those of the Institute.

Supporting Science

Antarctica New Zealand supports a range of activities in Antarctica and the Southern Ocean every year. Thirty to forty science projects involving around two hundred researchers from throughout New Zealand are supported each season, including collaborations with scientists from other countries.

New Zealand's influence in Antarctic issues is built on scientific understanding and the ability to predict impacts, direct and indirect, on Antarctica and the Southern Ocean. Antarctica New Zealand's science strategy—*New Zealand Science in Antarctica and the Southern Ocean (2003–2008)*—provides a framework to manage national research in the region.

Antarctica New Zealand's three major initiatives are the Latitudinal Gradient Project (LGP), Biodiversity of the Ross Sea (BioRoss), and an international drilling project, ANDRILL.

LGP takes advantage of the "natural laboratory" in the latitudinal gradient offered by the Ross Sea sector. The project combines many scientific disciplines to address biological responses to a changing environment and expand our knowledge of the coastal marine, inland aquatic, and terrestrial ecosystems in the region. This collaborative project is spread over a 10-year period; the first research work was begun at Cape Hallett in October 2003.

BioRoss was developed by the Ministry of Fisheries, Antarctica New Zealand, and the Ministry of Foreign Affairs and Trade as part of New Zealand's Biodiversity Strategy process. The objective is to develop a more complete inventory of the biodiversity in selected marine communities in the Ross Sea region and to enable better state-of-the-environment reporting.

New Zealand is the project manager for ANDRILL, a multinational drilling project aimed at improving understanding of Antarctica's role in global climate change from 65 Ma to the present. ANDRILL will provide records critical to understanding fundamental ice sheet behaviour and its influence on the global climate. The ANDRILL consortium comprises the USA, Italy, Germany, and New Zealand.

Environmental Stewardship

Antarctica New Zealand works closely with other countries and operators in the Ross Sea region and elsewhere, in order to minimize the environmental impact in Antarctica.

All activities in Antarctica are managed under the Protocol on Environmental Protection to the Antarctic Treaty, which Antarctica New Zealand translates into appropriate environmental standards for the activities it supports. An Environmental Management System based on ISO 14001 assists compliance with New Zealand legislation.

In 2001, Antarctica New Zealand published *Ross Sea Region 2001: A State of the Environment Report for the Ross Sea Region of Antarctica.* This is the first comprehensive stock-take of the region. It reports on the pressures human activities are placing on the environment and details the current management of these pressures. The report concludes that the Ross Sea region, despite a history of human involvement of nearly five decades, generally remains in a pristine condition. Developing priorities and potential projects from the report is now an important focus for Antarctica New Zealand.

Public Awareness and Education

The public awareness and education programmes are designed to increase awareness of New Zealand's activities in Antarctica.

The Artists to Antarctica Programme, partnered with Creative New Zealand, provides opportunities for artists to explore Antarctica in their work and increase understanding among New Zealanders of the values of Antarctica and its global importance.

Active education networks facilitate the development of curriculum-based education resources as well as increasing awareness of the importance of Antarctica to students at all levels.

Media visits to Antarctica inform the public about current activities in the New Zealand programme. The Invited Visitor Programme increases knowledge and understanding of the importance of Antarctica and the role of New Zealand.

Operations

Antarctic logistics is an integral aspect requiring ongoing cooperation with other Treaty partners. Antarctica New Zealand works cooperatively with the US and Italian Antarctic programmes to plan and coordinate the movements between Christchurch and McMurdo and on the ice.

International Representation

New Zealand is committed to the Antarctic Treaty and is a consultative party. Antarctica New Zealand is involved as part of New Zealand Government delegations to international forums and specialist networks, including the following:

- Council of Managers of National Antarctic Programmes (COMNAP)
- Antarctic Environmental Officers Network (AEON)
- Committee on Environmental Protection (CEP)
- Antarctic Treaty Consultative Parties (ATCM)

LOU SANSON and NATALIE CADENHEAD

See also **Antarctic Treaty System; Commonwealth Trans-Antarctic Expedition (1955–1958); Council of Managers of National Antarctic Programs (COMNAP); International Geophysical Year; Protocol on Environmental Protection to the Antarctic Treaty; Ross Island; Ross Sea; Scientific Committee on Antarctic Research (SCAR)**

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NORDENSKJÖLD, OTTO

Nils Otto Gustaf Nordenskjöld was born in Sweden on December 6, 1869, and as a schoolboy he expressed an interest in the geography of distant sites. His uncle, Adolf Erik Nordenskiöld, the leader of the first expedition to navigate the Northeast Passage, in *Vega* (1878–1880), provided further inspiration. In 1894, Nordenskjöld completed his doctoral degree at Uppsala University and held parts of a chair in mineralogy and geology, through which his interest in landscape formation and geohistory developed.

In 1895–1897, Nordenskjöld organised an expedition to Patagonia and Tierra del Fuego, partly to compare the biological, geological, and ice conditions of the northern and southern hemispheres. In addition to this, he carried out extensive mapping and studies of the Ona, one of the area's indigenous peoples. In 1898, Nordenskjöld visited the Klondike in Alaska, without any major financial or scientific success. Thereafter, he finalised his plans for an expedition to Antarctica, but was flexible as to timing and scientific objectives. Inspired by the 1895 and 1897 geographical congresses highlighting the need for exploration of Antarctica, Nordenskjöld engaged in fundraising and began to look for suitable expedition members. Meanwhile he prepared himself further with regards to organisation, logistics, and equipment. In the summer of 1900, he joined the Danish expedition to East Greenland under the leadership of Lieutenant Georg Carl Amdrup, in which Nordenskjöld accompanied the ship party led by Nicolaj Hartz. The ship was the whaler *Antarctic,* which Nordenskjöld shortly afterwards purchased.

From the beginning, Nordenskjöld planned an expedition with dual functions, enabling both scientific endeavours and whaling, and as a result he hired the experienced Norwegian whaling master Carl Anton Larsen as captain of *Antarctic*. With the Swedish South Polar Expedition, Nordenskjöld became the first Swede to carry out an expedition to the Antarctic mainland, 1901–1904. Nordenskjöld had, with some difficulties, found a suitable scientific team to work with studies in meteorology, geology, botany, zoology, and oceanography as well as mapping. Larsen was entrusted with the job of finding most of the crew members, amongst them several experienced whalers. To a certain extent, the sealing and whaling operations intruded on the scientific work, and consequently the ship party was relatively inactive for some periods of time. Nevertheless, valuable mapping, biological, and oceanographic work was carried out. At the land station, Snow Hill Island, systematic studies of climatic and ice conditions were pursued, fossils were collected, and contributions were made to the understanding of global ice conditions and land formation. Furthermore, the results foreboded theories on continental drift. Nordenskjöld and some of his fellow expedition members also made an attempt to establish the first Swedish whaling/science consortium for the Antarctic in 1911–1912, in cooperation with Great Britain (including the British Museum and the Royal Geographical Society) and Norwegian whaling interests.

In 1905, Nordenskjöld became professor in Economic Geography and Ethnography, and in 1923, he became the founder and head of the Gothenburg School of Economics. In 1913–1918, he was chairperson of the International Polar Commission and he was also elected as a member of several scientific societies in Sweden and abroad, where he developed his interest for scientific work in the Arctic. Nordenskjöld died on June 2, 1928, due to injuries incurred after being hit by a bus close to his home.

Lisbeth Lewander

See also **Larsen, Carl Anton; Swedish South Polar Expedition (1901–1904); Swedish South Polar Expedition, Relief Expeditions**

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NORTHERN GIANT PETREL

The northern giant petrel, *Macronectes halli* (order Procellariiformes), is a large, surface-nesting fulmarine petrel common to the sub-Antarctic region, that is remarkably similar to southern giant petrels *(M. giganteus)* in terms of life history, ecology, and breeding biology. Northern giant petrels also resemble southern giant petrels in that both species have large wingspans (1.5–2 m), stocky builds, and wings that are pointed, somewhat narrow, and designed for effortless soaring. Unlike southern giant petrels, however, northern giant petrels do not have a light or white phase, although their plumage may become lighter, especially on the neck and head, as individuals age.

Northern giant petrels have a circumpolar, exclusively peri-Antarctic breeding distribution between 44° S and 55° S, a zone between the Subtropical Convergence to the north and the Polar Front to the south. Only on the island of South Georgia do northern giant petrels breed south of the Polar Front. Juveniles of the species, however, disperse widely outside this breeding range, with individuals commonly occurring near the coastlines of the three southern continents (Africa, South America, and Australia) during the 5- to 11-year interval between fledging and recruitment into the breeding population. The breeding population is currently estimated at c. 11,200 pairs, with numbers increasing at some localities, and decreasing at others in response to anthropogenic factors such as disturbance, mortality due to commercial fishing bycatch, and variability in resource availability.

Foraging strategies are generally gender specific, with males and females showing greater tendencies towards land-based and oceanic feeding, respectively. Studies based on satellite telemetry demonstrated that male northern giant petrels tended to forage almost exclusively near Antarctic fur seal *(Arctocephalus gazella)* colonies, especially during the peak in seal carcass availability, while females during the same period generally continued to forage at sea, thus providing a variety of prey species to developing chicks. Because giant petrels are opportunistic predator–scavengers, the availability of carrion due to increasing seal and penguin populations near some breeding localities, especially at critical periods during chick growth and development, has likely contributed to localized population increases of northern giant petrels. It has been speculated that this dichotomy in resource use due to on-shore scavenging for carrion by males and pelagic foraging by females has effectively decreased the potential for breeding failures due to starvation, which is seen in other seabird species that specialize in fewer types of prey.

Northern giant petrels tend to nest in sheltered locations amongst tussock grass or on vegetated slopes. Individuals of this species lay a single egg between mid-August and mid-September, or approximately 6–8 weeks earlier than do southern giant petrels. Thus, although the two species may breed sympatrically at several locations, the timing of their breeding cycles ensures very little interbreeding. Eggs are incubated for approximately 60 days, with males taking a slightly larger share of incubation duties. Chicks fledge within 110–120 days and weigh 4–6 kg, with male fledglings often leaving the nest slightly heavier than females.

Despite what appears to be a relatively stable global breeding population of northern giant petrels, the proximity to, and increase of, commercial longline fishing still poses a significant threat to the species. This is due especially to the fact that young prebreeding individuals may repeatedly come in contact with fishing vessels during their many years spent at sea before they join the breeding population while they mature. Thus, despite an abundant prey base near breeding localities, mortality due to fishery bycatch may still seriously compromise the future stability of northern giant petrel populations throughout their range.

Donna Patterson-Fraser

See also **Polar Front; Seabird Conservation; Seabird Populations and Trends; Seabirds at Sea; Southern Giant Petrel**

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NORWAY: ANTARCTIC PROGRAM

Norway has a long history of whaling, exploration, scientific activity, and surveying in the Antarctic. Such activities motivated Norway's annexation of Bouvetøya in 1930, Peter I Øy in 1931, and Dronning Maud Land in 1939. Paralleling these territorial claims, Norway has played an important role in Antarctic cooperation, through long-term research and active participation in the development of the international legal framework concerning the management of Antarctica within the Antarctic Treaty System. Two of the postwar milestones in Norway's Antarctic research were the Norwegian-British-Swedish Antarctic Expedition (1949–1951) to Maudheim in Dronning Maud Land and the establishment of the Norway Station in Dronning Maud Land. This station was manned in the period 1956–1960 in support of the International Geophysical Year (IGY).

Following a 15-year hiatus, during which Norwegian activity was restricted to participation on expeditions organised by other nations, the first Norwegian Antarctic Research Expedition (NARE) took place in the austral summer 1976–1977. Three more NAREs followed in 1978–1979, 1984–1985, and 1989–1990. The summer station Troll Station, erected at Jutulsessen in Gjelsvikfjella in Dronning Maud Land in the austral summer 1989–1990, was the first Norwegian base established in Antarctica after the Norway Station. Since 1991–1992, following an agreement between Norway, Sweden, and Finland that committed each nation to organise an expedition every third year, Norwegian research and monitoring within fields of marine biology, geology, glaciology, and physical oceanography have been carried out annually during austral summers. Since 2000–2001, the Nordic collaboration has benefited from intercontinental flights between South Africa and Dronning Maud Land. Norway is now entering a new era in terms of logistics in Antarctica, through the establishment of a blue-ice runway at the research station Troll in Dronning Maud Land, and through an upgrade of Troll to winter-activity status from 2005.

Norway has, as a claimant state in the Antarctic, a responsibility for science-based management of the natural resources. Norwegian research activities are fundamental for the management of the natural resources in Norwegian Antarctic territories. In the coming years special focus will be on understanding the fundamental processes in Antarctic environments in relation to environmental variability and human impacts. This includes studies of topics such as climate modelling, paleoclimate, ocean circulation, marine ecosystems, the carbon cycle, tourism, and cultural heritage. Monitoring programmes including atmospheric studies, marine living resources (CCAMLR), meteorology, and human impacts will also be given high priority. Further, topographical and geological surveying in the Norwegian claimant areas will be continued.

The Norwegian Polar Institute is the principal supplier of scientific information on Norwegian polar regions for the central government administration, acting as its consultant on polar matters and helping to ensure that the environment is managed as efficiently as possible, in keeping with international efforts to promote sustainable development. The institute is the national manager and operator for the Norwegian Antarctic Program. It has the status of a directorate, and is responsible to the Norwegian Ministry of Environment, which is funding Norwegian Antarctic activities with about US$2.5 million per year.

Jan-Gunnar Winther

See also **Antarctic: Definitions and Boundaries; Antarctic Treaty System; Bouvetøya; Christensen Antarctic Expeditions (1927–1937); Geopolitics of the Antarctic; International Geophysical Year; Norwegian-British-Swedish Antarctic Expedition (1949–1952); Peter I Øy; Tourism**

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NORWEGIAN-BRITISH-SWEDISH ANTARCTIC EXPEDITION (1949–1952)

The Norwegian-British-Swedish Antarctic Expedition (NBSAE) was the first Antarctic expedition to be organized by a tripartite consortium. The idea for an expedition to Dronning Maud Land in the South Atlantic sector originated with Hans Ahlmann, professor of geography at the University of Stockholm. Ahlmann had observed that many glaciers in countries bordering the North Atlantic had been in retreat during the first half of the twentieth century, and wondered whether this was a local trend or perhaps part of some global change. In 1942, he had seen aerial photographs taken in 1939 by a German expedition to Dronning Maud Land in which ice-free areas appeared to have been recently exposed. Aware that glaciers are sensitive to climatic change, Ahlmann conceived the idea of an expedition to study the area.

Norway had formally claimed the sector between 20° W and 45° E. Inspired by Ahlmann, the Norwegian government decided in 1946 to mount an expedition, although not even 1 year had elapsed since the surrender of German forces in Norway at the end of the Second World War. Sweden agreed to participate, and Ahlmann approached the Royal Geographical Society in London with a view to British participation. This was forthcoming, and a tripartite committee began planning for a 2-year expedition to start in 1949.

The scientific objectives included glaciology, meteorology, geology, and mapping. As the first expedition to winter in the Atlantic sector of the continent between 57° W and 95° E (nearly half the coastline of Antarctica), it was felt that the program should be as broad as possible within the constraints of a small land party. Inland exploration would depend on dog transport supported by three Weasel tractors.

The expedition traveled in two ships. The 24,000-ton *Thorshøvdi* was a whaling factory ship on her way south for the 1949–1950 season whale fishing. *Thorshøvdi* sailed from Sandefjord, Norway on October 25, 1949, with five members of the expedition, sixty-two sledge dogs, and the tractors. *Norsel,* a sealer one-fortieth the size of *Thorshøvdi,* left Oslo on November 17, 1949 with the bulk of the expedition's cargo and the remainder of the staff. She also carried a five-man Royal Air Force group with two small Auster aircraft for reconnaissance. *Thorshøvdi*'s cargo, with her five expedition members and the dogs, were transferred to *Norsel* near the edge of the pack ice on January 14, 1950.

Under the command of Guttorm Jacobsen, *Norsel* spent 2 weeks working through pack ice before approaching the coast, which was found to consist of ice cliffs 20 m high. It took a week of searching with an aircraft on floats to find an ice dock low enough to unload the ship. Four hundred fifty tonnes of cargo were landed and then hauled to a point 3 km from the ice front, after which the ship departed with the air unit on February 20. Maudheim base was established on a floating ice shelf at 71°3′ S, 10°56′ W. A wintering party of fifteen men under the leadership of Norwegian John Giæver included six Norwegians, four Swedes, three Englishmen, one Australian, and one Canadian. Of these, the scientific staff comprised three glaciologists, two meteorologists, two geologists, and a surveyor.

While the meteorologists spent the following 23 months at Maudheim studying weather systems and the energy balance from the snow surface to altitudes of 20 km, glaciologists spent the first winter drilling to study the structure of the ice at depth. A local survey network was established to study the deformation of the ice shelf.

After the winter, a route-finding party traveled 300 km inland to a mountain area. On their return, all three Weasels were used to carry 10 tonnes to establish an advance base from which field parties would travel onward by dog sled. A four-man geology/survey party with three dog teams and a four-man glaciology party with two dog teams left Maudheim on December 19, 1950. The glaciologists determined ice temperatures at 10 m depth and the annual rate of snow accumulation at every camp site; and in several places they established survey networks to measure the rate of glacier flow. The geologists traveled far and wide to sample outcrops for geological mapping, and the surveyor developed a triangulation network to provide ground control for topographic mapping from aerial photographs.

A visit by *Norsel* after the first year brought a Norwegian aviation group and three new wintering staff. Survey flights were made to the inland mountain areas. One member of the first wintering party returned home with the flying group at the end of *Norsel*'s visit.

On February 24, 1951, 3 weeks after the ship left, one of the Weasels with four men on board accidentally drove over the ice front in a fog. Bertil Ekstrøm, John Jelbart, and Leslie Quar drowned. Stig Hallgren swam to an ice floe and was rescued 13 hours later after a dinghy was launched to recover him. Now only six men remained to man the base at Maudheim.

The last field party returned to Maudheim with their dogs on May 30 after living in tents for 24 weeks without a break. However, Alan Reece, one of the geologists, was now blind in one eye after being hit by a rock fragment on March 11. Ove Wilson, the young Swedish doctor, was advised by radio to remove the damaged eye as a precaution against infection of the patient's good eye. After the training of four assistants, none of whom had ever seen an operation, the damaged eye was successfully removed.

During the second winter, the glaciologists obtained ice cores to a depth of 100 meters in the ice shelf, a world record at the time, and resurveyed the ice deformation network. Preparations were made for the second sledging season, during which, in addition to continuing the first summer's work, a party of three men would penetrate as far inland as possible to measure ice thickness by seismic sounding. In the event, the seismic party reached a point 620 km inland. Ice thicknesses greater than 2500 m were found, indicating that in this area, a fjord landscape extended far inland under the ice sheet.

Norsel returned to Maudheim for the last time on December 22, 1951, bringing a Royal Swedish Air Force flying group to complete the aerial surveys. Maudheim was abandoned on January 14, 1952, and the expedition reached Southampton, England on February 18.

The scientific results of the expedition exceeded expectations. The glaciological studies showed that the ice sheet was neither in retreat nor advancing. The finding that the inland ice was much thicker than expected led to the conclusion that the amount of ice on Antarctica must represent the principal factor controlling world sea level. The geological work found evidence (interpreted decades later in the light of the new science of plate tectonics) that indicated that Dronning Maud Land had once been joined to southern Africa. The meteorological studies showed the extent to which the Antarctic ice sheet affects world climate. The survey triangulation covered an area of some 60,000 km^2, and aerial photography extended this to about 100,000 km^2. Finally, medical research on expedition members led to a new understanding of the effects of prolonged isolation.

Six volumes of scientific results were published, together with a set of topographic maps and many papers in scientific journals. The success of the expedition helped to end the series of competing national expeditions that had characterized the first half of the twentieth century. It paved the way for continued international cooperation and laid a foundation for the Antarctic phase of the International Geophysical Year of 1957–1958.

Charles Swithinbank

See also **Antarctic Ice Sheet: Definitions and Description; Climate Change; Dogs and Sledging; Field Camps; German South Polar *(Schwabenland)* Expedition (1938–1939); History of Antarctic Science; Ice Sheet Mass Balance; Ice Shelves; International Geophysical Year; Pack Ice and Fast Ice; Plate Tectonics; Ponies and Mules; Surface Energy Balance**

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NORWEGIAN *(FRAM)* EXPEDITION (1910–1912)

Roald Amundsen's ambition in life was to be a feted and successful polar explorer, and the climax of his career was to be the expedition to the South Pole, 1910–1912, an expedition that came about as a result of a quirk of fate.

After his successful traversal of the Northwest Passage, 1903–1906, the North Pole was Amundsen's next obvious goal. He announced that he would carry out a repeat and extension of Fridtjof Nansen's famed drift over the Arctic Basin. Nansen had intentionally let his specially constructed ship, *Fram,* freeze into the ice to drift through the Arctic Ocean from east to west in 1893–1896. The expedition had not, however, quite attained the Pole, something that Amundsen now intended to accomplish. He obtained Nansen's permission for the use of *Fram* on the condition that scientific research be given a key role. In 1909, the Norwegian Storting (Parliament) granted Amundsen 75,000 kroner to prepare *Fram* for the new North Pole expedition. King Haakon agreed to be the expedition's patron, and a number of wealthy private donors contributed, but Amundsen still had to seek Nansen's help to obtain loans for the remainder of the expenses.

Amundsen's plan was upset in September 1909, when both Frederick Cook and Robert E. Peary claimed that they had reached the North Pole, Cook in 1908 and Peary earlier in 1909. Interest in sponsoring Amundsen's expedition dwindled, and he realised that he had to achieve another major goal—becoming the first man to reach the South Pole—in order to generate interest for his Arctic drift plans. Arriving second was not in his nature. The change of plans was kept secret, including from Nansen, whose backing had been crucial, and from most of the participants, until the ship arrived at Madeira, which was the last stop before the Antarctic. The men were given the choice to continue to the Antarctic or to return home; they all stayed. The subsequent announcement of Amundsen's change of plans caused an international sensation not only because he had withheld the information from the king and Nansen, but because a British expedition led by Robert Falcon Scott was also planning an attempt on the South Pole. Amundsen's short telegram to Scott—"Beg to inform you Fram proceeding Antarctica. Amundsen"—shocked the British, and his choice to establish his winter base in the same general region of the Antarctic as Scott's earlier and intended site came to be interpreted as unfair play.

Amundsen's greatest attribute as a leader of polar expeditions was his meticulous attention to detail in planning. His time on the Belgian Antarctic Expedition, 1897–1899, and with the Netsilik during his navigation of the Northwest Passage had given him ideas and practical experience with regard to optimal equipment for long dog-sledge journeys. Reading previous Antarctic expedition reports gave him warnings and advice, including the fact that the Bay of Whales at 78°38′ S seemed to be a stable part of the Ross Ice Shelf (or Great Ice Barrier, as it was known at the time) on which to establish his base, thus putting him closer to the South Pole than Scott at his base in McMurdo Sound. All his equipment was specially made according to detailed specifications, and both provisions and participants were carefully chosen.

Fram was to deliver the shore group and spend the Antarctic winter on a scientific cruise in the southern Atlantic under the command of Captain Thorvald Nilsen, before fetching the shore party the following southern summer. On shore for the South Pole expedition would be nine men, including Amundsen, most of them with the title of general workers. Two men from his previous expedition were included, the dog driver Helmer Hanssen and the cook, Adolf Lindstrøm. Sverre Hassel had learned dog driving with Otto Sverdrup in northeast Canada on the second *Fram* expedition, and Olav Bjaaland was an excellent skier, while Hjalmar Johansen had accompanied Nansen when he left *Fram* on his "sprint" toward the Pole in 1895–1896. Oscar Wisting, Kristian Prestrud, and carpenter Jørgen Stubberud completed the wintering group.

When *Fram* left Kristiania (Oslo) on August 9, 1910, most of the crew still thought they were sailing round South America to reach the Bering Strait and a drift over the Arctic Ocean. Many wondered at the 100 Greenland dogs onboard—why take them over the Equator when they could be fetched from Alaska? The large prefabricated cabin was also puzzling for a drift in Arctic ice. At Madeira, on September 6, they were told of the "detour" to the South Pole, and on January 13, 1911, they reached the Bay of Whales. It took a month to unload and establish the shore base, Framheim, with the dogs transporting goods between the ship and the base site. On February 2, Scott's *Terra Nova* sailed up beside *Fram* and could see how efficient this means of transport was. *Fram* sailed to 78°41′ S in the bay before leaving, thus becoming the ship that at that point had been both farthest north and farthest south.

During the autumn, large food and fuel depots were established by dog-sledge and ski journeys at each degree of latitude up to 82° S, and these were marked by an almost foolproof system of flags planted east to west out from the depots, so that they could hardly be missed even in poor weather. At the same time, valuable travel experience was acquired. The winter was spent perfecting and modifying equipment and extending the base with snow tunnels and rooms for various storage and work purposes, while Amundsen worked on the question of rations. Seals and penguins provided a fresh meat supply, not least for the dogs, while the dogs in their turn were carefully calculated to become a meat supply themselves on the trip to and from the Pole. In this way the weight of food to be taken was cut down, and scurvy was made less likely.

Amundsen's only grave mistake during the expedition was to try to start too early for the Pole, occasioned by a fear of losing the prize to Scott. September 7 was too early for travelling: the temperature was down towards –50°C and both men and dogs froze. The return to base a week later was a rout, with Amundsen running first. He could have lost men, but Johansen "swept them up" from behind and rescued both them and ultimately the Pole expedition. Heavy criticism from Johansen, particularly in front of the others, was not tolerated by Amundsen, who demoted him from the Pole group and sent him on a mapping expedition under Prestrud to King Edward VII Land instead. It was a clear snub for the experienced Johansen, who had brought the younger Prestrud home from the early start. Amundsen's revenge was underlined by his sending Johansen off in disgrace when the expedition returned to civilisation.

A new start was made on October 19, with Amundsen, Hanssen, Hassel, Bjaaland, Wisting, and fifty-four dogs. Only Amundsen did not drive his own sledge. The use of skis, dog sledges, experienced men, dogs for food, and carefully established and marked out depots made the perfect combination, and the journey to the Pole and back was carried out without significant problems. When Amundsen departed his first depot at 81° S, Scott was just leaving his winter base. By November 16, Amundsen's group was across the Ross Ice Shelf and had the Transantarctic Mountains in front of them. Ernest Shackleton had already shown a way to the South Pole, but by starting farther west on the Ross Ice Shelf, Amundsen had to find a new way up to the Polar Plateau. He chose the glacier that he named after one of the sponsors, Axel Heiberg, and 4 days later, with forty-two dogs, they reached the Plateau. The names "The Devil's Glacier" and "The Devil's Dance Floor" show, however, that the route was not easy. The dogs had done the worst part of their job. The group was at 85°26′ S, with 440 km left and no more heavy climbs. Twenty-four dogs were shot, some for food immediately and some for later. The eighteen best were kept for the next part of the journey. After 4 days stuck in their tents because of a snowstorm, the party continued, although still in bad weather and sledging conditions. At 87° S the conditions improved, and on December 14 they reached their goal. Here Amundsen declared how strange it was to stand at the South Pole, when his real goal was actually the North Pole.

The group had beaten Scott by a month. Together they planted the Norwegian flag and called the expanse around them Haakon VII's Plateau. Neither this claim nor Prestrud's at King Edward VII Land was followed up by the Norwegian government. Amundsen noted the day of arrival as December 15, since he had forgotten that they had crossed the International Date Line on their voyage. They stayed there for 3 days, in order to observe the position as correctly as possible, making ski trips from the Pole in the other three directions to be sure that they had actually reached the spot, and moving their camp slightly farther south. When they headed north, they left behind a small tent containing some extra equipment and letters to King Haakon and Scott. Scott was asked to take the King's letter back with him. The photograph Scott's party took of Amundsen's tent at the Pole a month later would ultimately prove that both expeditions had actually reached the spot.

Amundsen's group now had sixteen dogs pulling two sledges. By January 6, 1912, they were back on the Ross Ice Shelf after an exciting skiing experience back down the glacier. They had more than enough food for the return journey, and the clothes and equipment functioned well. They arrived back at Framheim on January 25, earlier than expected after a total journey of c. 3000 km in 99 days. *Fram* had already arrived on January 8, after her oceanographic expedition in the southern Atlantic, and the shore party, including the remaining thirty-nine dogs, left on January 30. It took 5 weeks to reach Hobart, Tasmania, where the news of the expedition's success could be released.

Prestrud, Johansen, and Stubberud had left Framheim on November 8, 1911, and had reached King Edward VII Land on December 2. They were back at Framheim on January 10, after mapping and making observations in the previously unknown territory. This side expedition and its results were, however, not of great interest to Amundsen. Five days later the Japanese *Kainan Maru* expedition surprised them by visiting the Bay of Whales.

Amundsen was now supposed to continue with his expedition to the North Pole, as he had promised Nansen. However, time passed as he held lectures in Australia, New Zealand, Europe, and America, which helped to cover old debts and new expenses. *Fram* was left too long in the warm waters off South America, and was too worm-eaten to survive a new battle with the ice in the Arctic Ocean. Then WWI broke out. It was not until 1918 that his next expedition finally left in *Maud*.

Amundsen had not made any pretence of conducting scientific research in the Antarctic. It was the conquest of the Pole alone that was his motivation, and being the first there. Time was, therefore, essential, as he had no idea of Scott's progress. The expedition did have other significant results, however: it proved the superiority of ski and dog-sledge expeditions in polar areas, it opened and mapped a different route to the Polar Plateau from Shackleton's and Scott's, and it gave knowledge to future expeditions about equipment, nutrition, and travel planning. On the home front, Amundsen's success also gave the new independent nation of Norway a world-famous name and a deed to be proud of.

Susan Barr

See also **Amundsen, Roald; Belgian Antarctic *(Belgica)* Expedition (1897–1899); British Antarctic *(Terra Nova)* Expedition (1910–1913); British Antarctic *(Terra Nova)* Expedition, Northern Party; Hanssen, Helmer; Japanese Antarctic Expedition (1910–1912); Ross Ice Shelf; Scott, Robert Falcon; Shackleton, Ernest; Wisting, Oscar**

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NORWEGIAN (TØNSBERG) WHALING EXPEDITION (1893–1895)

Henrik Johan Bull (1844–1930), a Norwegian who emigrated to Australia, read the report by James Clark Ross of numerous right whales in the Ross Sea and became convinced of the commercial possibilities of whaling in Antarctic seas. After 3 years of unsuccessfully trying to raise funds for a whaling expedition to the Ross Sea, Bull visited Svend Foyn, the pioneer of modern whaling, in Norway. Within 15 minutes, the 84-year-old Foyn had agreed to provide funding and a ship, a 226-ton whaler originally named *Kap Nor* but to be renamed *Antarctic*. Foyn appointed Leonard Kristensen captain, with Bull as manager.

Unfortunately, the division of duties was not properly established, which led to subsequent problems between the two men.

William Speirs Bruce, who subsequently joined the Dundee Whaling Expedition (1892–1893), and Eivind Astrup, who had travelled with Peary in Greenland, asked to join as naturalists, but were unable to reach the ship in time. Carsten Borchgrevink, another Norwegian who had emigrated to Australia, also applied for the post of naturalist, but was shipped as seaman.

Antarctic sailed from Tønsberg, Norway on September 20, 1893, and headed for Îles Kerguelen, where oil and skins of 1600 elephant seals were taken. After calling in at Melbourne, where Bull remained behind to finalize preparations for the voyage to the Ross Sea, *Antarctic* went whaling. One right whale was taken, but the ship ran aground at Campbell Island and repairs were needed on its return.

On September 26, 1894, *Antarctic* set sail again and headed south via Campbell Island, where a few fur seals were taken. Svend Foyn Island was named, but it proved to be a huge iceberg. On the following day, November 7, the propeller worked loose and the ship made for Port Chalmers, New Zealand, under sail.

The final departure from New Zealand was on November 30, Victoria Land was sighted on January 17, 1895, and a landing was made on Possession Island, where Ross had landed 53 years earlier. Borchgrevink discovered a lichen, the first plant to be found south of the Antarctic Circle. *Antarctic* achieved a farthest south of 74°00′ S, and, on January 24, 1894, a boat party landed at Cape Adare. At the time this was believed to be the first landing on the continental mainland of Antarctica, but American sealers had already done so in the 1820s.

The expedition now returned northward. Attempts to go sealing at the Balleny Islands were prevented by bad weather. One sperm whale was caught off Tasmania, and Melbourne was reached on March 12.

Commercially, the expedition had been a failure. It was equipped to catch slow-moving right whales, and attempts to catch fast rorqual whales were unsuccessful. No right whales were found in the Ross Sea, and it has been suggested that Ross had been mistaken in his identification. The expedition is best known for the apparent "first landing on the continent." Kristensen claimed to have been the first ashore, but Borchgrevink maintained that he had leaped out as the boat grounded on the beach. Later, Alexander von Tunzelman, a seaman, declared that he had held the boat steady while the others disembarked. Bull and Borchgrevink started to plan a second expedition, but Bull withdrew after he found Borchgrevink claiming credit for the first expedition's achievements.

Robert Burton

See also **Balleny Islands; Borchgrevink, Carsten E.; Bruce, William Speirs; Dundee Whaling Expedition (1892–1893); Foyn, Svend; Kerguelen Islands (Îles Kerguelen); Ross, James Clark; Whaling, History of**

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OASES

Antarctic oases are variably sized ice-free areas on the coast of Antarctica. The term started use in October 1936 at an ice-free area that was analogous to a desert oasis. Alfred Stephenson, a meteorologist with the British Graham Land Expedition, camped on the eastern side of Alexander I Island at Ablation Camp, wrote: "It seemed we had suddenly come into an oasis, for instead of the usual mass of snow with occasional patches of rock there were large valleys of exposed rock with scarcely any snow to be seen" (Stephenson 1938: 194–195).

Since then, the term oasis has been refined by Shumskiy (1957) to incorporate a meteorologically based meaning that emphasised the presence of an ablation zone between the land and surrounding ice. An Antarctic oasis, therefore, is a substantial ice-free area that is separated from the ice sheet by a distinct ablation zone and is kept free from snow by ablation due to low albedo and positive radiation balance. This meaning was permanently enshrined by Solopov (1967) in his monograph *Oazisy v Antarktide (Oases in Antarctica)*. This definition of oasis thus excludes nunataks (even comparatively large massifs), coastal bluffs, peninsulas, off-shore islands, and areas where topographic damming of ice (rather than ablation) has led to their ice-free nature. The Victoria Land Dry Valleys and the Amery Oasis/Beaver Lake area of Mac.Robertson Land fall into this last category. The formation or presence of oases has no relationship with a "local paucity of precipitation" reported by Bölter et al. (2002: 8). Smith (1988, 1997) also developed a biological definition of oasis that is not in common usage.

In addition to these constraints, most oases have four other geographical traits in common. First and most importantly, they lie beside a deeply incised outlet glacier that creates substantial drawdown in the ice surface. This drawdown reduces the flux of the ice sheet over a potential oasis, allowing deglaciation to occur. Second, all oases have erosional (e.g., striation) and depositional (e.g., till and moraine) evidence indicating former cover by an ice sheet. Third, because of the typically disorganised drainage patterns, there are abundant lakes. Fourth, because of the habitat afforded by rock crevices, sediment, and shallow ponds, the oases are home to abundant terrestrial, lacustrine, and marine life. Most oases, including Vestfold, Larsemann, and Stillwell, abut the open ocean, but Bunger and Schirmacher oases lie behind ice shelves.

Bunger Hills ($\sim$950 km^2, max 160 m asl) is bounded by the ice sheet to the east, glaciers to the south and west, and the Shackleton Ice Shelf to the north and northwest. Within these boundaries lie $\sim$480 km^2 of land and a number of marine inlets. The hills were first sighted from a distance by members of the Western Base of the Australasian Antarctic Expedition (1911–1914), but they were thought to be an island. The true nature of the hills was discovered by the 1946–1947 US Navy Operation Highjump, and the first visitation was made by navy pilot, David Bunger, who landed a seaplane on one of the lakes in February 1947. Richard E. Byrd (1947) described the area as "an island suitable for life...in a universe of death." The First Soviet Antarctic Expedition visited the oasis in 1956, with the establishment of Oasis (Oazis) Station at the end of that year. At the end of 1958, Oasis Station was transferred to the Polish expeditions, under which it was renamed Dobrowolski. This facility has operated intermittently since that time, including the construction in 1987 of additional buildings a few hundred metres to the west of Dobrowolski. In 1985–1986, Australian expeditioners established Edgeworth David Base, which consisted of a small number of fibreglass shelters, a few kilometres west of Dobrowolski. There are contrasts in the geography of Bunger Hills. To the south and east, the rock is less weathered, the terrain is more rugged, sediments are fewer, plants are more abundant, and the lake water is fresher. To the northwest, sediments are much more abundant, rock is strongly weathered in places, and there are brackish lakes. Less than 5% of Bunger Hills is covered by snow and ice. The presence of dozens of Weddell seals in the marine inlets implies that the sea ice breaks out annually, and most freshwater lakes thaw annually. Saline lakes are rare in Bunger Hills, and the few that exist are frozen during winter. Birds, particularly snow petrels and skuas, are abundant.

The largest truly coastal oasis is Vestfold Hills (420 km^2, max 170 m asl). Vestfold Hills is bounded by Sørsdal Glacier to the south, the ice sheet to the east, and the ocean to the west. Discovered and photographed from the air in February 1935 by the captain and crew of the Norwegian whaling vessel *Thorshavn,* this area of rolling brown hills with striking mafic dyke swarms was named after Vestfold County, in southern Norway. This section of Princess Elizabeth Land was named the Ingrid Christensen Kyst, in honour of the wife of the whaling magnate Lars Christensen. Caroline Mikkelsen has the distinction of being the first woman to step ashore at Vestfold Hills, even though it was a small island just offshore. There was a long absence until 1955–1957, when both Soviet and Australian expeditioners visited Vestfold Hills, the latter to establish Davis Station on January 13, 1957. Apart from a 4-year hiatus from January 1965 to February 1969, Davis has operated continuously. Like Bunger Hills, less than 5% of Vestfold Hills is covered by snow and ice. While eastern Vestfold is rugged and sediment poor but rich in vegetation, western Vestfold has subdued topography and abundant sediment, but is poor in vegetation. Sea salt drives this pattern. Vestfold Hills hosts a Pliocene diatomaceous sediment in Marine Plain that contains *in situ* whales and other vertebrate fossils. Vestfold Hills is renowned for its hypersaline lakes, including Deep Lake, which has a salinity nine times that of seawater and a lake surface nearly 50 m below sea level. Some hypersaline lakes, including Club, Deep, and Lebed, do not freeze, even in mid-winter. Freshwater lakes are also common, but perennially frozen lakes are rare. Vestfold has abundant wildlife, including Adélie penguin rookeries, elephant seal haul-out beaches, snow petrels, Wilson's storm petrels, South Polar skuas, and rare giant petrel nests.

Larsemann Hills (50 km^2, max 180 m asl) was discovered and photographed by the Lars Christensen expedition of 1936. Consisting of two main peninsulas, Larsemann is bounded by the ice sheet to the south, Dalk Glacier to the east, and ocean elsewhere along its irregular boundary. The hills were visited again by Australian surveyors in 1957, but it was not until 1987 that the summer-only Law Base (Australia) was established. The Soviet stations Progress 1 (1988–1990; site now remediated) and Progress 2 (1990–), and the Chinese Station Zhong Shan (1989–) followed. Glacial erratics are relatively rare in Larsemann Hills, and moraines, while present, are few. Hilltops are typically bare and strongly eroded. Terrestrial plants, penguins, and seals are rare, while the numerous rock crevices host snow petrels. Skuas are found particularly around station buildings. Most lakes are freshwater and annually frozen, and host relatively rich ecosystems of algae and aquatic moss. Lakes near to the ice dome on Stornes (the western peninsula) appear to be perennially frozen and almost devoid of the rich growths of plants found on Broknes (the eastern peninsula).

Stillwell Hills ($\sim$96 km^2, max 340 m asl) is a coastal area of rugged, low hills forming a peninsula and a number of smaller islands. The Hills are bounded to the south by the ice sheet, to the west by a small outlet glacier, and to the north and east by sea. The outlet glacier calves into sea ice that is pinned in behind small islands. Fold Island ($\sim$40 km^2) lies immediately to the north of the main peninsula of Stillwell Hills and is separated from it by a narrow channel only a few hundreds of metres wide. An emperor penguin rookery beside Fold Island indicates the presence of perennial sea ice there. The main peninsula is 18% covered by icefields, which fill the valleys and abut lakes that appear to be perennially frozen. Geological investigations were carried out by D. S. Trail in 1961. While there are no bases at Stillwell Hills, proximity to Mawson Station (Australia) means that summer access is straightforward.

Schirmacher Oasis (34 km^2, max 220 m asl) lies in an embayment in the ice sheet, with the Novolazarevskaya ice shelf to the north. The oasis probably owes its existence to Wohlthat Massif, some 80 km to the south, diverting continental ice from the area. The oasis is elongated east–west, and is only a few kilometres wide in several places. Numerous ponds and lakes are dammed behind snow and firn fields, and most lakes thaw annually. The oasis was first discovered from the air in February 1939 by pilot Richard Heinrich Schirmacher, and the first station to be built there was Novolazarevskaya (USSR) in 1961. German scientists, supported by the Soviet Antarctic Expeditions in Schirmacher since 1976, established a laboratory that became Georg Forster Station (Germany) in 1987. In 1989, Maitri Station (India) was built a few kilometres from Novolazarevskaya Station. Georg Forster Station was closed in 1993. The oasis is frequented by nesting seabirds, including skuas, snow petrels, Wilson's storm petrels, and Antarctic petrels. Adélie penguins have been known to attempt to nest but are rarely successful.

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See also **Adélie Penguin; Antarctic Petrel; Australasian Antarctic Expedition (1911–1914); Australia: Antarctic Program; British Graham Land Expedition (1934–1937); Byrd, Richard E.; China: Antarctic Program; Christensen Antarctic Expeditions (1927–1937); Christensen, Lars; Dry Valleys; Emperor Penguin; Germany: Antarctic Program; India: Antarctic Program; Poland: Antarctic Program; Oases, Biology of; Russia: Antarctic Program; Skuas: Overview; Snow Petrel; South Polar Skua; Southern Elephant Seal; Southern Giant Petrel; Streams and Lakes; United States Navy Developments Projects (1946–1948); Weddell Seal; Wilson's Storm Petrel**

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OASES, BIOLOGY OF

An oasis is generally defined as a fertile area in a desert, occurring where the water table approaches or reaches the ground surface. However, in an Antarctic context, oases have been variously construed by scientists as being either dry or wet and either large or small snow-free areas on the continent. The most widely accepted concept is based on local climatic, topographic, geomorphologic, and hydrologic criteria, the most important being that they remain largely snow free due to negligible precipitation and high ablation rates in summer. Most of the larger oases are at or near the edge of the continental ice sheet near the coast, some being separated from the sea by ice shelves. Smaller oases occur at higher altitudes far inland. However, not all ice-free areas constitute oases. If such areas are extensively colonized by vegetation, this implies that the local climate, environment, and water availability are suitably favourable for widespread plant development, and thus do not comply with the concept of Antarctic oases. Some scientists use the term "oasis" to describe a wide range of ice-free sites surrounded by permanent ice, particularly in the region of the Antarctic Peninsula and offshore islands, and often with prominent vegetation. However, such areas are not oases in the conventional sense, and are not considered here.

From a biological or ecological point of view, it is the wet area within an otherwise desert-like environment that is the oasis, and not the ice-free desert *in toto*. This concept may be defined as follows: "An area of restricted size where there is surface water, at least for part of the summer, and where local topography provides a favourable microclimate, allowing a concentration of microbial and plant species to develop relatively complex communities in an otherwise arid and barren desert landscape."

The McMurdo Dry Valleys of southern Victoria Land is the largest ice-free area in Antarctica, covering c. 4000 km^2, and comprises a complex system of broad valleys separated by high mountain ranges and surrounded on all but its coastal boundary by glaciers. The Dry Valleys experience very low summer temperatures and negligible precipitation, although occasional snowfall occurs on the upper slopes of the valleys, permitting very sparse lichen growth. Although it is essentially a desert, there are several large and small lakes ranging from seasonally ice-free to permanently frozen to a depth of many metres, while others are highly saline, especially at depth. During summer, streams flow from melting glaciers towards some of the lakes, although many fail to reach them before drying up. Away from these water sources, the coarse, sandy, gravelly, porous soils are extremely dry and largely incapable of sustaining life in any form. The most biologically rich habitats are the seepage areas below some of the glacier snouts. Here melt water spreads out over the adjacent ground, at some sites covering up to several thousand square metres, and maintaining a wet substrate for a short period during mid- to late summer. These areas support a diversity of plants and microorganisms, and an associated invertebrate fauna. By far the greatest biodiversity is found in the aquatic environment, where algae and cyanobacteria predominate. One of the most intensively researched sites is the Canada Stream, a diffuse area of melt water flowing from the Canada Glacier to Lake Fryxell in Taylor Valley. Here, and in other temporary streams entering the lake, there are several distinct algal communities. The central areas of the channels are dominated by orange-brown mats of the cyanobacteria genera *Oscillatoria* and consolidated mats of *Phormidium*. The edges of these channels are usually dominated by loose black mats of another cyanobacterium genus, *Nostoc*. Filamentous growths of the green alga *Prasiola* form green-colored mats in some of these streams. In all these communities diatoms are also abundant.

Beyond the wettest areas several simple communities of terrestrial vegetation are formed by small patches of diminutive species of moss (notably *Bryum* spp., *Hennediella heimi, Sarconeurum glaciale*). The drier short turves and cushions of moss are sometimes colonized by a few species of crustose lichens as well as by black encrusting cyanobacteria. Crustose lichens also occasionally colonize stones at the margin of the wet areas. However, within a metre or two of this marginal zone the ground becomes extremely dry and visibly barren. Within the moss, algae, and cyanobacteria communities there are associated microfauna. The only macroscopic invertebrates are occasional mites and springtails associated mainly with moss or beneath stones where they feed on algae and fungi. At the microscopic level, nematode worms, tardigrades, rotifers, and protozoans may be locally frequent amongst moist moss and associated with algae and cyanobacterial mats in aquatic habitats.

Other extensive (c. 100–500 km^2) ice-free areas include Bunger Hills (Queen Mary Land), Vestfold Hills, and Larsemann Hills (Princess Elizabeth Land). These have an undulating topography of low hills, broad valleys, and basins with many streams and freshwater and saline lakes and ponds. As with the Dry Valleys, wet areas adjacent to some of the lakes and below glaciers and ice fields provide a habitat for mosses, algae, and cyanobacteria. Because the climate in these areas is less severe than in the Dry Valleys, some 7–10 degrees of latitude farther south, biological diversity is greater. Extensive stands of *Nostoc* and *Phormidium* dominate seepage areas, and stands of moss can reach 100 m^2 or more and may comprise one or several species, including *Bryum* spp., *Ceratodon purpureus,* and *Schistidium antarctici,* with a few less frequent species occasionally associated. Rocks in melt channels sporadically splashed by water sometimes support thalli of the foliose lichens *Umbilicaria aprina, Physcia caesia,* and *Xanthoria elegans,* and occasional crustose species. Beyond the influence of ground water, vegetation becomes restricted to epilithic lichen communities, but these are not strictly components of the oases.

There are many small (10–100 km^2) ice-free sites where life is restricted mainly to isolated seasonal wet areas (e.g., Ulu Peninsula, James Ross Island; Seymour Island; Ablation Valley and Mars Oasis, Alexander Island; Edmonson Point and Beaufort Island, Victoria Land; Schirmacher Oasis, Dronning Maud Land; Langhovde and Skarvsnes, Enderby Land). Even at this level the oases are discrete, and some have more complex biological communities (e.g., Ulu Peninsula, the northernmost of the Antarctic biological oases).

On a much smaller scale there are other types of biologically rich microsites within arid, barren landscapes. Although not strictly oases, they do fulfill some of the criteria that permit a diversity of life to exist. One of these categories is the nutrient-enriched cliffs and screes (talus) below breeding colonies of sea birds, notably snow and Antarctic petrels, in inland mountain ranges. Such areas can cover several hundreds of square metres and support several species of brightly coloured nitrophilous lichens, especially species of *Acarospora, Caloplaca, Candelariella, Rhizoplaca,* and *Xanthoria,* occasional mosses, and the green alga *Prasiola crispa*. Being well adapted to drought and low temperatures, these lichens are dependent more on the nutrients than on free water, as they have the capacity to absorb moisture from the atmosphere. A similar type of microoasis occurs on James Ross Island, where many ancient carcasses and skeletons of seals occur up to several kilometres from the shore. The low nutrient status, dryness, and instability of much of the island's terrain prevent plant colonization, but nutrients leaching from these cadavers permit numerous mosses and lichens to grow on and around them. Geothermal ground near the summits of the three active volcanoes in Victoria Land (Mount Erebus, Mount Melbourne, and Mount Rittmann) also act as microoases where a very few bryophytes and algae have established. Here, the warm ground and steam provide a favourable habitat, sometimes <1 m^2, while beyond these hotspots conditions are too severe for colonization.

RONALD I. LEWIS-SMITH

See also **Algae; Algal Mats; Antarctic: Definitions and Boundaries; Antarctic Petrel; Colonization; Dry Valleys; Dry Valleys, Biology of; Ice Shelves; Lichens; Microbiology; Mosses; Nematodes; Oases; Polar Desert; Protozoa; Ross Island; Rotifers; Snow Petrel; Streams and Lakes; Tardigrades; Vegetation**

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OATES, LAWRENCE EDWARD GRACE

Captain L. E. G. Oates holds a unique place in the history of Antarctic exploration, due not only to being part of Robert Falcon Scott's party who died after attaining the South Pole, but because of the way he sacrificed his life on the tragic return journey in order to help save his comrades. He was immortalised by his laconic final words: "I am just going outside, and may be some time."

Lawrence Edward Grace Oates was born on March 17, 1880, at Putney, London, the eldest son of William and Caroline Oates (née Buckton). Although more popularly known as "Titus" after the infamous anti-Catholic conspirator, relatives called him Laurie. He was a member of a distinguished and wealthy family that lived at Gestingthorpe Hall, the manor house at Gestingthorpe, Essex, from 1891, and can trace its lineage back 1000 years.

Oates was a sickly child who was dominated and spoilt by his formidable mother Caroline. He was given a fine education, including a brief spell at the Remenham Place preparatory school and 2 years at Eton (1894–1896). But he failed miserably at school and never passed a single examination, largely because of dyslexia. After numerous futile attempts to pass entry exams into the army, in 1898 he enlisted in the militia corps, the Prince of Wales's Own West Yorkshire Regiment.

Oates was subsequently gazetted to the 6th Inniskilling Dragoons, the elite cavalry regiment, on April 6, 1900, after the outbreak of the Boer War. He was recommended for the Victoria Cross, the highest military honour, for one act of courage that left him badly wounded and with one leg shorter than the other. However, Oates grew disenchanted with the army during peacetime duties in Ireland, Egypt, and India (1902–1909). He was an expert horseman and an adventurous, old-style cavalry officer more suited to a chivalrous age, and he struggled to come to terms with the military reforms and the changing face of warfare in the early twentieth century.

Oates was promoted to the rank of captain in November 1906, but was anxious to leave the army when he learned about Scott's South Pole expedition in 1909. In his eagerness, he paid £1000 (approximately £50,000 in today's terms) to the expedition's funds and was given responsibility for the horses, which were central to Scott's plans. But he was not asked to select the poorly suited animals, which he described as the "greatest load of crocks I have ever seen." Oates proved to be one of the most popular men on the expedition, but he clashed a number of times with Scott over the purchase and deployment of the inadequate ponies.

Oates, a reserved, aristocratic man of great courage, was an outsider as the only solider in the navy-dominated expedition. But he worked tirelessly on the march toward the South Pole, getting the last of the horses 400 miles (640 km) across the Great Ice Barrier (now known as the Ross Ice Shelf) to the foot of the Beardmore Glacier. He was selected for the final Polar Party because Scott wished to see the army represented at the South Pole. But Oates was already in serious decline from fatigue and frostbite when Scott made his selection and wanted to return to base camp. A closer inspection of his fitness might have excluded him from the final party.

With his comrades, Oates reached the South Pole on January 17, 1912, but weakened rapidly on the return journey. Initially he kept his condition hidden, but in early March he revealed badly frostbitten feet and hands. He deteriorated rapidly during the next two weeks, with his feet swollen by acute frostbite and worsening gangrene. He begged to be left behind and on March 16 or 17, 1912, he crawled from the tent to commit suicide, unable to cope any longer. It was his thirty-second birthday, and Scott wrote: "We knew it was the act of a brave man and an English gentleman." His body was never found, but his death became a symbol of noble sacrifice.

MICHAEL SMITH

See also **British Antarctic *(Terra Nova)* Expedition (1910–1913); British National Antarctic *(Discovery)* Expedition (1901–1904); Dogs and Sledging; Ponies and Mules; Scott, Robert Falcon; Wilson, Edward**

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OCEAN RESEARCH PLATFORMS AND SAMPLING EQUIPMENT

Throughout history, scientific research in the Southern Ocean has been limited by the remoteness of the region, its severe weather, and the presence of ice. Once on site, scientists have typically sampled the ocean by lowering selected instruments on appropriate wires, but a frozen surface can complicate this process or render it dangerous, particularly during winter months. In spite of these problems, early explorers nearly always sampled the ocean, taking cores of the sediments; collecting fish, invertebrates, and benthic (bottom-dwelling) fauna; and measuring temperature and salinity to characterize the physical state of the seawater. Although simple equipment was employed, the data provided a first glimpse into the sub-ice environment and the ecosystems functioning there. Much of the knowledge gained about the Southern Ocean through the middle of the twentieth century was obtained on the *Discovery* investigations.

The advent of icebreakers in the latter half of the twentieth century made it feasible to work in the pack ice, but mostly in the austral summer and with a primary mission of supporting coastal stations. As such, scientific sampling was a relatively low priority, although those ships were outfitted with rudimentary laboratories, winches, and sampling equipment. Shortly after the International Geophysical Year, the US National Science Foundation converted a military transport ship into a full-time research vessel, the USNS *Eltanin,* from which multidisciplinary surveys were made over broad areas of the Southern Ocean during the 1960s and 1970s. Subsequent demand for more knowledge finally resulted in the construction of a new breed of ship, ice strengthened but lacking the power of turbine- and nuclear-driven icebreakers. These research vessels included *Polar Duke, Nathaniel B. Palmer,* and *Laurence M. Gould* (US), *Aurora Australis* (Australia), *James Clark Ross* (Great Britain), and *Polarstern* (Germany). These ships can stay at sea for 50+ days, can berth and feed 25+ scientists plus crew, and have modern laboratories and sampling equipment, along with a capacity to load and deliver substantial quantities of supplies to stations and field camps.

The equipment these vessels carry on a given expedition will depend on the type of research to be conducted, but a primary tool for many oceanographers is the CTD/rosette, which measures *c*onductivity (salinity), *t*emperature, and *d*epth (pressure), and can also retrieve samples of water from any depth. As this package is lowered on an electrically conductive cable, the data from these measurements are fed to the operator's console, where they are plotted versus depth as the CTD descends or returns to the ship. Water samples are acquired using plastic "Niskin" bottles attached to the circumference of the rosette and triggered from the surface when the desired depths are attained, usually on the return trip to allow a rapid and continuous sampling of physical parameters during the descent. Once on board, the seawater is drained from the bottles and analyzed using standard laboratory procedures for salinity (to monitor the conductivity probe), nutrients (mainly nitrate, phosphate, and silicate), suspended particles, or a variety of dissolved ions, metals, gases, and organic compounds. Additional devices can be plugged into the CTD package for concurrent data display and recording. Many of these instruments are optical, sensing the total clarity of the water, the amount of phytoplankton (microscopic suspended algae), chlorophyll fluorescence, and the natural light transmitted into or scattered within the water. Other types of samples are acquired with a variety of bottom corers, nets, and trawls for collecting swimming, drifting, and benthic organisms. Surface seawater is commonly pumped aboard for laboratory analyses while ships are underway.

Most ships are equipped to sample the water column and seafloor using acoustic devices. The most basic of these is the simple echo sounder, which measures the time delay between transmission of a "ping" of sound into the water and its arrival back at the surface, having been reflected by organisms in the water and from the seafloor. The frequencies employed vary according to the task, with high frequencies (100 kHz or above) used to assess fish and krill populations, and low frequencies (12 kHz) used to measure the water depth. Even lower frequencies, less attenuated by seawater, are used to investigate the layering of sediments within the seafloor. Good resolution of the upper layers is provided by 3.5 kHz, but in order to see deep into the sediments, geophysicists utilize "airguns" to generate pulses of sound in the 100-Hz range. These pulses echo back from the seafloor, from structures deep within the sediments, and from bedrock below the sediments, and are recorded using a towed array of hydrophones. More sophisticated echo sounders utilize multiple sound pulses and phased detection of the returns to acquire three-dimensional images of a swath along the seafloor. Geophysicists also use ship-borne gravimeters to measure local gravity anomalies caused by embedded masses or isostatic disequilibrium caused by plate tectonic motions, and towed magnetometers to map anomalies produced as the oceanic plates spread apart and the Earth's reversing magnetic field is recorded in the solidifying igneous rocks.

Another instrument mounted in most ships' hulls is the Acoustic Doppler Current Profiler (ADCP). This device consists of three or four transducers facing downward but mounted at slight angles relative to one another, sending out pulses of high-frequency sound (usually 150–1200 kHz) into the ocean and receiving the returns from particles suspended in the water. From the timing (distance from the source) and frequency shift (due to the Doppler effect of the moving particles), an instantaneous profile of the three-dimensional flow is recorded. To obtain absolute flow values, the ship's motion relative to the water and its pitch, roll, and heave must also be separated from the signal using data from sensors for that purpose. In regions of extensive sea-ice cover, these and other instruments are often deployed on bottom-moored arrays, with recorders that must be recovered at a later date. The instrument array typically consists of a heavy anchor (sometimes one or more steel train wheels), an acoustic release, wire or synthetic rope, and hollow glass spheres at the apex of the mooring to provide the buoyancy necessary to keep the array upright and facilitate recovery. The array is deployed by streaming the flotation spheres behind the ship while paying out the wire with its attached instruments, and finally dropping the anchor over the intended deployment site. Recovery is accomplished by sending a coded command to the acoustic release, causing it to release its grip on a chain attached to the anchor and allowing all but the anchor and chain to rise to the sea surface.

Instrumentation on moored arrays can include most of the equipment normally associated with ship-based sampling, or more specialized equipment. One common item is the sediment trap, which can collect either a single, time-integrated sample, or multiple, sequential, time-series samples. Particles are intercepted as they settle from the upper water column toward the seafloor where they would become sediment, and the biogenic components are analyzed for plankton and nekton activity. Some instruments are capable of measuring dissolved nutrients and other parameters, or preserving samples of the seawater and its contents. The latest development in this field is the cabled observatory, where a suite of instruments is installed on the seafloor and connected by a cable to a research station ashore. The cable provides power to the underwater package and delivers data from it to the land station and from there via the internet to computers in scientists' laboratories. Researchers can control the instruments and receive data in real time from anywhere in the world, while educators, students, and the general public can experience the Antarctic environment without the need to travel there.

Some sampling requirements demand instrumentation that moves independent of a ship or fixed mooring, and this can be free drifting, tethered, or autonomous. Drifters are used either to track the motion of the water itself or to acquire time-series measurements in a parcel of water as it circulates, and periodically transmit location and measurements to orbiting satellites. Tethered remotely operated vehicles (ROVs) are often used to provide the scientist with a virtual presence in the ocean where manned submersibles are impractical or unsafe (e.g., beneath sea ice, icebergs, and shelf ice). ROVs incorporate thrusters, video systems, and sensors that are manipulated by a technician aboardship through the vehicle's tether. These vehicles have been used to study organisms feeding on algae embedded in the ice and living on the sea floor, and regions where glacier calving fronts interact with the ocean and seabed. Where the tether presents an unacceptable hindrance to maneuverability or range, autonomous undersea vehicles (AUVs) are used. These rovers incorporate large battery packs and thrusters, and range in size from small enough to be operated from an inflatable boat to very large, requiring a crane and special handling system. AUVs that lack any mechanical means of propulsion are referred to as gliders. A buoyancy regulation system causes the vehicle to alternate between heavier and lighter than seawater, while movable "wings" cause the vehicles to be propelled forward during descent and ascent. This porpoising motion allows data collection in two dimensions: along a prescribed course using only the energy required by the buoyancy system, and that associated with data transmission through a satellite during surfacing intervals.

Satellites are also used to acquire sea-surface data such as passive radiation emitted from the ocean and sea ice, and ocean color related to plankton biomass. Much of this type of data can now be acquired in real time aboard ship, and is increasingly relied upon by modern expeditions for navigation in ice and weather, and for the location of choice sampling sites. These are all examples of technologies now being applied in studies aimed at better understanding the Antarctic environment, as well as in pressing concerns related to the increase in carbon dioxide in the atmosphere and oceans. Since this increase impacts seawater chemistry and organisms living in the sea, measurements are particularly needed in the remote Southern Ocean to adequately determine baseline values and monitor changes over time.

VERNON L. ASPER

See also **Antarctic Surface Water; Discovery Investigations (1925–1951); Ice Shelves; Pack Ice and Fast Ice; Remote Sensing; Southern Ocean: Biogeochemistry**

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OFFICE OF POLAR PROGRAMS, NATIONAL SCIENCE FOUNDATION, USA

The Office of Polar Programs is the day-to-day manager of the United States Antarctic Program. Some thirty of the office's scientific, engineering, and managerial staff work full time on the Antarctic (others are involved in the National Science Foundation's Arctic research program). The Antarctic staff represents 2.5% of the foundation's roster; the program it administers spends about 5% of the Foundation's $5.7 billion annual budget (2004 figures).

Dividing its time between the Antarctic and the seventh floor of the National Science Foundation headquarters building in Arlington, Virginia, the Antarctic staff manages the USA's scientific research and operational support in Antarctica and the Southern Ocean. But neither the Office of Polar Programs nor its parent foundation is an Antarctic institute. The field work is performed mainly by university scientists who have been awarded foundation grants and by operational support specialists who are employed with firms that have won National Science Foundation contracts. The US military has a substantial logistics role.

Responsibilities of the Office of Polar Programs include these functions:

- Annual preparation of plans and budget for consideration within the executive branch of the US Government and for review and appropriation by the US Congress
- Development of scientific goals for Antarctica, obtaining advice from the science community, and communicating these goals to the community
- Receipt of proposals for research and education projects from US universities, other research institutions, and federal agencies; evaluation of these proposals for relevance to program goals,

scientific merit, and logistics feasibility; and granting of funds (as available) to these institutions for performance of the projects in Antarctica and completion of analysis upon return
- Detailed planning of logistics, and transmittal of logistics requirements and funds to elements of the Department of Defense and to the US Coast Guard
- Facilities management, design, planning, engineering, construction, and maintenance
- Development and management of a contract with a commercial firm for operation of Antarctic stations and research ships and related services, including construction
- Development and implementation of safety, environment, and health programs for US activities in Antarctica
- Arrangement of cooperative scientific and logistics programs with other Antarctic Treaty nations
- Designation of a senior US representative in Antarctica and on-site management of the field programs in Antarctica
- Serving as a clearinghouse of information regarding Antarctic records, files, documents, and maps maintained within agencies and nongovernmental organizations.

In fiscal 2002, the office made 228 new grants to start Antarctic research projects, workshops, or analyses. In the 2001–2002 season, seventy-eight research institutions (mainly universities) throughout the United States were involved in field investigations in the Antarctic; scientists from these institutions conducted 148 research projects during the austral summer, and some of the projects continued through the 2002 austral winter. These numbers are roughly typical for any given year. Additional projects not involving fieldwork were conducted at the grantee research institutions in the United States.

The scientists obtained the grants (which were awarded, actually, to their employing universities) through a competitive process involving anonymous review by scientific peers and review by operational experts to establish the feasibility of supporting the research out in the field. This evaluation typically begins when proposals written in response to a foundation program solicitation arrive 15 months before a project goes to the Antarctic. A proposal received, for example, in June 2006 normally would be considered for support in the Antarctic no earlier than the 2007–2008 austral summer.

Operational support in the Antarctic is provided by a major contractor to the foundation; for the years 2000–2010 it is Raytheon Polar Services Company, Centennial, Colorado, other contractors, and the US military.

While the United States has no central Antarctic institute, the Office of Polar Programs does fund specialized Antarctic facilities whose counterparts in another nation might be part of that nation's Antarctic institute. These facilities include the National Ice Core Laboratory, Denver, Colorado; the Antarctic Marine Geology Research Facility and Core Library, Florida State University, Tallahassee, Florida; the Antarctic meteorite collection at the Johnson Space Center, Houston, Texas; a polar rock repository at The Ohio State University, Columbus, Ohio; an Antarctic Resource Center (maps and aerial photographs) at the US Geological Survey, Reston, Virginia; and the Antarctic Bibliography at the American Geological Institute, Alexandria, Virginia.

The National Science Foundation can commit funds for US participation in international Antarctic research only after peer review of proposals that it has received. Funds normally are not awarded to non-US institutions.

Other Participating Federal Agencies

Several other US agencies support Antarctic research—notably the National Aeronautics and Space Administration (satellite operations, satellite-derived and balloon-launched research); the National Oceanic and Atmospheric Administration (ozone research, climate monitoring at the South Pole); and the US Geological Survey (mapping). The agencies coordinate their Antarctic operational requirements with the Office of Polar Programs.

The Department of Defense provides military logistics, reimbursed by the foundation, comprising shipborne cargo between the United States West Coast and McMurdo Station (Military Sealift Command), shipborne fuel delivery to McMurdo (Military Sealift Command), airlift (primarily C-17) between Christchurch, New Zealand, and McMurdo (Air Mobility Command), LC-130 Hercules (ski-equipped) airlift in Antarctica (109th Air Wing, Air National Guard), cargo ship loading and unloading (Navy Cargo Handling and Port Group), and the aviation technical services of weather forecasting, air traffic control, and ground electronics maintenance (Space and Naval Warfare Systems Center).

The Department of Homeland Security (through the US Coast Guard) provides icebreaker services, reimbursed by the foundation: channel breaking of sea ice in advance of the fuel and cargo ships, escorting the supply ships into and out of McMurdo, and other assistance, including science project support.

The Department of the Interior's Office of Aircraft Services provides procurement assistance, contract administration, and inspection for commercial aircraft services contracted to the US Antarctic Program.

The Department of State formulates foreign policy direction relating to the US program and conducts foreign relations regarding Antarctica. It chairs the Antarctic Working Group—a subgroup of the Interagency Working Group on Global Environmental Affairs that formulates policy guidance for US activities under the Antarctic Treaty. Other members of the group are the National Science Foundation, the Department of Defense, and other federal agencies as appropriate.

Historical Development of the Office

The National Science Foundation's first Antarctic assignment was for funding of US planning and scientific participation in the 1957–1958 International Geophysical Year. Starting with fiscal 1954, only 4 years after it was established, the Foundation provided these funds to the National Academy of Sciences, a longstanding advisory body chartered by the US government, which in turn awarded them to participating scientists. The US Navy separately funded and managed operational support and logistics.

In 1959, the government decided to continue its support of Antarctic research indefinitely and formed the United States Antarctic Program, asking the foundation to manage it. The foundation set up an Office of Antarctic Programs; it began awarding research funds directly to scientists and coordinating operational needs with the Navy. The Academy started a Committee on Polar Research (later renamed the Polar Research Board), which the foundation funds, to advise the foundation.

In 1970, the President centralized government funding of the Antarctic program, including the Navy's role, at the foundation. About then, also, an Arctic responsibility was added and the office name was changed to Office of Polar Programs.

With centralized management came a gradual shift from military to civilian performance of many of the Antarctic operational functions. A Presidential memorandum in 1982 formalized the change. Over the years, consolidation increased the effectiveness and efficiency of research, for the military units were able to focus on their strengths and turn over the functions of science support and station operations to foundation contractors specifically oriented to these specialized tasks. The US military itself consolidated its remaining Antarctic functions. In 1998, the Navy withdrew from a long and distinguished career in the Antarctic as it turned over its then-principal Antarctic duty—flying ski-equipped LC-130 airplanes—to the New York Air National Guard, which already had a similar mission in Greenland.

Formal reviews in 1996 by the President's National Science and Technology Council, and in 1997 by a National Science Foundation external panel, revalidated the President's 1982 decision. The reviews recommended indefinite continuation of the United States Antarctic Program, along with its centralized management by the foundation's Office of Polar Programs.

GUY G. GUTHRIDGE

See also **Antarctic Treaty System; Council of Managers of National Antarctic Programs (COMNAP); International Geophysical Year; McMurdo Station; United States: Antarctic Program**

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National Science Foundation Polar Programs. http://nsf.gov/dir/index.jsp?org=OPP

US Antarctic Program External Panel. *United States in Antarctica*. http://nsf.gov/publications/pub_summ.jsp?ods_key=antpanel

OPERATIONAL ENVIRONMENTAL MANAGEMENT

Focus on the environmental aspects of Antarctic operations has increased significantly during recent decades. This has happened in parallel with the general increase in global environmental awareness. It also reflects a greater understanding of the impacts that operations have on the science that they support. The managers of Antarctic programmes have instituted operational procedures to minimize these impacts and provide Antarctic researchers with the best possible conditions. These efforts have been guided by the Antarctic political and legal system, which has placed environmental management high on the agenda during recent years.

The Legal and Political Framework for Operational Environmental Management

The desire to minimize environmental impacts from operations has been a concern from the start of scientific research in the Antarctic and has been clearly reflected in the many recommendations adopted by the Antarctic Treaty Parties through the years. Many of the recommendations have been developed on the basis of advice from the Scientific Committee on Antarctic Research (SCAR), which has ensured that the needs of the scientific community have been heard in the effort to maintain the value of the area for scientific research.

Already in 1961, the parties to the Antarctic Treaty had agreed to measures to conserve flora and fauna (Recommendation I–VIII), including, for example, recommendations regarding operations of aircraft and vehicles near concentrations of seabirds and marine mammals. In 1975, the Antarctic Treaty Parties adopted Recommendation VIII–11 (Man's Impact on the Antarctic Environment), containing a code of conduct that set minimum environmental standards for operations in Antarctica, including specifying standards for waste disposal. It also provided Antarctic operators with guidelines for the planning of major Antarctic projects, in essence stipulating the first environmental impact assessment requirements in Antarctica.

With time, the initial basic recommendations were further developed and tightened. Recommendation XII–3 (1983), for instance, gave national organizations responsible for Antarctic activities a clear obligation to scrutinize the plans for any scientific activity they planned to conduct, including the planned provision of logistic facilities to support such activity, in order to determine whether the planned activities were likely to have significant impacts. Recommendation XV–3 (1989) built on and tightened the earlier waste-disposal requirements and stipulated that the amount of wastes produced, or disposed of, in Antarctica should be reduced to the maximum extent possible so as to minimize impact on the Antarctic environment and minimize interference with scientific research or other legitimate uses of the Antarctic.

In October 1991, the Antarctic Treaty Consultative Parties adopted the Protocol on Environmental Protection to the Antarctic Treaty (the Protocol). The Protocol incorporated a number of the earlier recommendations regarding environmental management, including provisions for environmental impact assessment (Annex I), the conservation of Antarctic fauna and flora (Annex II), waste disposal and waste management (Annex III), the prevention of marine pollution (Annex IV), and area protection and management (Annex V). The Protocol provides a comprehensive legal and political framework for environmental operational management in Antarctica. The comprehensiveness of the Protocol and the overarching aim it sets out gave impetus for a whole new thinking with regard to operations in the Antarctic, and operators have seen further merit in reducing their impact in Antarctica.

The coming into the force of the Protocol prompted many operators to review their ongoing activities in Antarctica with the aim of improving operations and procedures affecting the environment, such as those related to waste management, fuel storage, and sewage treatment (see, for example, Argentina, 1998).

The Operational Framework for Environmental Management

In 1988, more or less parallel to the development and adoption of the Protocol, the national Antarctic programme operators joined forces and established the Council of Managers of National Antarctic Programmes (COMNAP) to facilitate liaison between the managers of national agencies responsible for the conduct of logistics operations in support of Antarctic science. One of COMNAP's aims is to enhance the national Antarctic programs' environmental stewardship in Antarctica through exchange of information and experience, development of manuals and guidelines, and consideration of common operational problems.

In the 1990s, many Antarctic operators appointed or identified persons within their organizations who would have special responsibility to follow up on the application of the provisions of the Protocol in the operations of their programme. In 1996, these Environmental Officers (EOs) moved COMNAP to form the Antarctic Environmental Officers Network (AEON) in order to provide a forum for the exchange of information, experience, and ideas about practical environmental management issues. The objectives of AEON are primarily information exchange and the promotion of a mutual understanding on the practical application of the Protocol in Antarctic operations.

During the past decade or so, COMNAP has developed comprehensive procedures and guidelines on operational aspects that are relevant in the context of Antarctic operational environmental management. Some examples of these guidelines include the following:

- Guidelines for Oil Spill Contingency Planning (1992)
- Recommended Procedures for Fuel Oil Transfer at Stations and Bases (1992)
- Recommendations for Spill Prevention and Containment of Fuel at Stations and Bases (1992)
- Guidelines for the Reporting of Oil Spill Incidents which Occur in Antarctica (1993)
- Antarctic Environmental Monitoring Handbook (2000)

Practical Aspects of Operational Environmental Management

Permits and Environmental Impact Evaluations

Those responsible for operations in Antarctica must normally report any new activity to the appropriate national authorities. Permit and authorization requirements vary between countries, depending on the specifics of their national legislation. Common for all are the environmental impact assessment (EIA) requirements provided for in the Protocol, which requires that all activities in Antarctica be planned and conducted so that they inflict as little as possible negative impact on the environment. EIA procedures are detailed in Annex I of the Protocol. Such procedures ensure that appropriate environmental management and mitigation procedures are identified for the activity. Since the coming into force of the Protocol, most Antarctic operators have put in place procedures for environmental impact assessments and are actively pursuing these requirements.

Activities that are likely to have little if any impact on the environment (including most science events) require a preliminary assessment procedure before they are allowed to proceed. For more substantial activities likely to have some environmental impacts associated with implementation, an initial environmental evaluation (IEE) is normally required. Although all activities are assessed on an individual basis, the types of activity that trigger the IEE level are often similar between operators, and usually encompass activities such as removal of stations, fuel storage instalments, upgrading of stations, installment of larger equipment (e.g., scientific, communication), and transport upgrading.

When an activity is expected to have more than minor or transitory impact, a comprehensive environmental evaluation (CEE) is required. Only a handful of CEEs have been developed to date. The types of activities considered have so far been mostly related to construction of new stations and large-scale research activities. Examples since 1998 include the following:

- Scientific ice drilling and construction of a field camp (Germany)
- Project Ice Cube at South Pole Station (United States)
- Upgrading of the Norwegian summer station Troll to a permanent station (Norway)
- Construction and operation of a Czech scientific station (Czech Republic)
- Water sampling from the subglacial Lake Vostok (Russia)
- Development and implementation of surface traverse capabilities (United States)
- Scientific drilling and infrastructure provision for the Cape Roberts (CRP) and ANDRILL Projects (New Zealand)

The process of assessing environmental impacts is complex and challenging. To aid operators in implementing the assessment process in a coherent manner, the CEP adopted "Guidelines for Environmental Impact Assessment in Antarctica" in 1999, which set out a step-by-step approach to the assessment process. The guidelines are meant to aid operators in their endeavours to assess the environmental impacts of their operations in a methodological and structured manner, identifying impacts and dealing with mitigation issues.

In 2001, COMNAP, through its AEON, analyzed a number of IEEs developed by national operators in order to achieve a better understanding of how the EIA process is being used by national Antarctic programmes, and to identify strengths and weaknesses in the preparation of IEEs (COMNAP 2001). Through the analysis it was found that different aspects of the EIA processes are being done well while other aspects can be further improved. The analysis noted, in particular, weaknesses with regard to the actual evaluation of environmental impacts, the key component of the EIA process. Establishing a methodological approach to evaluation of environmental impacts is therefore recognized as a particular challenge that operators will continue to consider. Despite the challenges still remaining, the environmental impact assessment process has nevertheless clearly aided operators in considering environmental aspects of the operation, and how these best can be dealt with.

Waste Management

Until relatively recently, waste-disposal practices in Antarctica were more or less similar to those elsewhere in the world, with open dumps, landfills, and burning, and, more particular for Antarctica, dumping of waste on the sea ice during winter, as it would float away and sink during the summer. Sewage was normally burned or discharged with little or no treatment straight into the sea. With the adoption of the Protocol, the focus on waste management increased significantly. Annex III of the Protocol sets waste management standards, including waste minimization; consideration of waste storage, disposal, and removal; returning waste to the organising country; and cleaning up sites of past activities. Operators have, over the last 2 decades, developed stringent procedures and routines to handle waste in accordance with these standards, and have developed detailed waste-management strategies. For example, the short summary of Antarctica New Zealand's waste strategy states that the organization "will minimize, reuse and recycle waste generated by its activities as far as practicable and will ensure that waste is disposed of with minimal environmental impacts. Waste management planning will examine the use, where appropriate, of alternative technologies, materials and disposal options, and identify areas of past activity which require future clean up and/or remediation" (Antarctica New Zealand 2004).

Strategies and policies have been developed into plans, guidelines, and handbooks to provide practical procedures for the handling, storage, and disposal of waste and to provide procedures for the day-to-day implementation of the strategies and policies developed. Plans typically include detailed procedures for the proper separation, handling, storage, transport, and disposal of all wastes generated, including field activities. Policies are also in place to promote waste minimization and increase waste recycling. The complexity of the waste strategies varies from operator to operator and according to the complexity of the operations. Comprehensive waste-classification schemes have been developed, both to promote recycling of the waste and to enable recording of amounts to facilitate studies aimed at evaluating the environmental impact of the operations.

Today all operators remove most of the waste from Antarctica. However, sewage and food wastes still remain a challenge and are often treated and disposed of at the site. At the coastal stations such waste is often discharged untreated (or only macerated) into the sea or into ice pits. Studies have shown that such effluent can have some local impact. Thus, aiming at minimizing the impacts even further, more and more operators are installing sewage-treatment plants for treatment of the sewage before discharge, and collection of sludge/dried solid matter for removal from Antarctica.

Discharge of sewage at inland stations has proven to be more challenging. At some of these stations such waste is discharged into cavities, so-called "sewage bulbs," in the ice. Other stations have installed incinerator toilets, from which the remaining ash is removed from Antarctica. Although the Protocol specifically prohibits it, several inland stations have found it necessary, due to operational challenges, to discharge wastewater directly on ice-free ground, normally after some treatment. The challenge of handling liquid waste at inland bases has been noted, and COMNAP has, on this basis, investigated the question of best practice, reaching the conclusion that the proper treatment of wastewater depends on the specific situation and that therefore there is no single "best practice."

Fuel Use, Storage, and Management

Virtually all operators in Antarctica operate a range of vehicles for transport of personnel and materials, as well as for mechanical works. Most stations are also supported by vessel operations, and some by aircraft. Ships, aircraft, and vehicles, as well as stations and field camps, operate predominantly on fossil fuels. With the large quantities of fuels being stored, transported, and consumed, fuel spills constitute one of the highest operational environmental threats to the Antarctic environment (COMNAP 2002). Operators endeavour to minimize the threat by limiting consumption, ensuring appropriate storage and handling, and establishing response mechanisms in the event of spills.

At stations and in the field, leaks from hosing, fittings, and seals are a common cause of fuel spills. A rupture/breach of an uncontained fuel-storage tank has the potential to cause major spills. The worst-case scenario for a sea-based environmental emergency would be a vessel that sinks, and breaks up, releasing its bunkers or cargo fuel.

Many operators have, within the new environmental framework, over the last decades evaluated and improved their fuel-storage and -handling systems. When systems are upgraded, secondary containment at fuel-storage sites are normally installed. For example, at McMurdo Station, the US program has recently upgraded fuel-storage facilities so that most bulk-storage tanks now have some form of secondary containment. At nearby Scott Base all single-skinned fuel-storage tanks were replaced with double-contained tanks between 1998 and 2000. Electronic fuel-leak monitoring systems have been installed at some stations (e.g., the South African Base SANAE IV).

Aware that the reduction of risk of emergencies or accidents is best achieved through effective measures on preparedness, emergency response action, and contingency planning, the Antarctic Treaty Consultative Parties agreed in 1998 to adopt the numerous COMNAP guidelines on fuel oil handling, spill prevention and containment, contingency planning, and reporting of oil spills as a framework for fuel management for operations in Antarctica.

Energy Management

In addition to the risk of fuel spills, the use of fossil fuels entails the release of both greenhouse gases and pollutants into the atmosphere. An aim for Antarctic operators is therefore to reduce fuel consumption through conservation and use of alternative energy sources. The use of alternative energy sources is on the increase. Solar energy is used in several places, mostly at the smaller stations, such as Lake Hoare Camp (US) in the Dry Valleys and Wasa Station (Sweden) in Dronning Maud Land. Wind energy is also used, although mostly on a small scale, at several stations, for example, Neumayer Station (Germany), Juan Carlos I (Spain), and Syowa (Japan). In 2004, the Australian Antarctic Division initiated the first serious attempt by any operator to use wind power generation in Antarctica on a large-scale basis when the installation and commissioning of two wind turbines was completed at Mawson Station.

Flora and Fauna, and Introduction of Microorganisms

Harmful interference with flora and fauna, for example flying or landing helicopters, using vehicles or vessels, or using explosives in a manner that disturbs concentrations of birds and seals is, in accordance with Annex II of the Protocol, prohibited. On this basis, operators have instituted procedures to ensure that flora and fauna are not disturbed as a result of their operations. Environmental codes of conduct have been developed by most operators, covering issues such as vehicle use, pedestrian traffic, camping, etc. Several operators have also instituted guidelines for aircraft operations in order to minimize environmental impact from such operations. At ATCM XXVII in 2004 it was noted that the potential for harmful disturbances to concentrations of birds makes it important to provide pilots with guidelines that would prevent or minimize the damaging impact, and on this basis the Antarctic Treaty Consultative Parties adopted "Guidelines for the Operation of Aircraft near Concentrations of Birds in Antarctica," which will provide operators with further guidance in minimizing environmental impact from their operations.

Annex II of the Protocol also requires operators to take necessary precautions to prevent the introduction of microorganisms not present in the native flora and fauna. Introduction of exotic organisms such as plants, seeds, insects, spiders, and microorganisms is a potential threat to the Antarctic environment, and could irrevocably change the natural environment and wildlife. Some operators, such as the Australian Antarctic Division, have instituted extensive procedures to prevent the introduction of microorganisms through quarantine practices based on inspection measures, administrative measures, and on-site management activities, while others are still in the process of assessing the risk and the necessary precautionary procedures.

Monitoring

Monitoring of the impacts of activities in Antarctica is an integral part of environmental operations. The Protocol is an important basis for determining monitoring requirements. The most common types of monitoring studies being undertaken by Antarctic operators include (1) contamination in near-shore coastal ecosystems; (2) atmospheric pollutants associated with station activities; (3) quantity and quality of sewage and waste-water discharges, (4) levels and fate of hydrocarbons in soil and/or water; and (5) population counts and/or breeding success of Antarctic birds (COMNAP 1998). Many national programs have developed systematic monitoring programs that are specific to their operations. Other operators have not begun or are only in the early stages of program development. COMNAP, through its AEON, is developing practical guidelines to assist operators in developing and designing monitoring programs for particular operations, and has also developed a technical monitoring handbook (2000) to facilitate comparative studies across operators.

Training

Operators in Antarctica recognize that education and training are essential in improving the environmental management in operations, and most operators have included environmental management in their training framework, although the extent, form, and content vary between operators. Training and education are often multitiered, conducted both before departure, while travelling, and on arrival in Antarctica. A number of tools are used for training/education purposes, such as printed codes of conduct, videos (such as *Caring for the Environment in Antarctica—A Guide to Your Responsibilities,* produced by Antarctica New Zealand), web-based training tools, and specialized training courses for specific (high-risk) activities (e.g., the Antarctic Oil Pollution Control Course, organized by Oil Spill Response Ltd. (OSRL) and the British Antarctic Survey). COMNAP has adopted a voluntary checklist for environmental training to assist operators in developing the environmental aspects of their training program.

Operational Environmental Management in the Tourism Industry

The Environmental Protocol also applies to tourism and nongovernmental activities. Environmental awareness has always been a key element of tourism operations in Antarctica, and already in the 1970s operators active in the region recognized the need for standardisation of operating procedures that would protect the vulnerable environment and initiated relevant codes of conduct. In 1991, the International Association of Antarctica Tour Operators (IAATO) was formed to promote the highest possible standards of travel in Antarctica, and is today invaluable in providing an operational environmental management framework for tour operators in the region. IAATO has over the years developed an extensive number of procedures and guidelines in order to assist their members to practice appropriate, safe, and environmentally sound activity in the Antarctic in accordance with the Environmental Protocol. The IAATO framework rests on, and further specifies and develops the provisions of, Recommendation XVIII–1, *Guidance for Visitors to the Antarctic and Guidance for Those Organizing and Conducting Tourism and Non-Governmental Activities in the Antarctic,* adopted by the Antarctic Treaty parties in 1994 (and developed on the basis of IAATO's original operating guidelines from 1991).

To minimize impacts of activity on shore, IAATO has instituted, amongst other things, regulations and restrictions on the number of people that can be ashore at a site at the same time, guidance with regard to staff-to-passenger ratios, and restrictions on the size of vessels that can visit particular sites. IAATO has also developed site-specific guidelines for sites that are visited regularly to ensure that activity at these sites takes into account the particular sensitivities of these sites. A set of marine wildlife–watching guidelines to provide guidance to operators with respect to minimizing impact on the marine fauna due to cruise activity has been developed, as well as have guidelines for helicopter operations in order to minimize impacts on sensitive bird and mammal populations. IAATO is notably in the forefront in promoting practical practices for boot and clothing decontamination in order to reduce the risk of introducing nonnative species and of transmission of disease to the sites visited by tourists.

IAATO requires extensive postvisit reporting from members and maintains an extensive database with information on tourism activities in Antarctica over the last 15 years. This is one of the most important information bases the Antarctic Treaty parties have at their disposal in the context of assessing human pressure on the Antarctic environment and monitoring environmental impacts.

BIRGIT NJÅSTAD

See also **Antarctic Treaty System; Appendix: Text of the Antarctic Treaty; Appendix: Text of the Protocol on Environmental Protection to the Antarctic Treaty; Australia: Antarctic Program; Aviation, History of; Conservation of Antarctic Fauna and Flora: Agreed Measures; Council of Managers of National Antarctic Programs (COMNAP); McMurdo Station; New Zealand: Antarctic Program; Pollution; Protocol on Environmental Protection to the Antarctic Treaty; Scientific Committee on Antarctic Research (SCAR); South Africa: Antarctic Program; Tourism; United States: Antarctic Program**

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OZONE AND THE POLAR STRATOSPHERE

Ozone is a compound of oxygen containing three atoms, instead of two as in the oxygen gas that sustains life. It was discovered in 1839 by a Swiss chemist, Christian Friedrich Schonbein. In high concentration, ozone is a bluish-green gas, with very strong oxidising properties. It is a toxic, irritating gas, often encountered in surface air pollution episodes, when it can trigger asthma and irritate mucous membranes. Dry air consists of 78% nitrogen and 21% oxygen and normally trace amounts of other gases, principally argon, water, and carbon dioxide. The concentration of ozone is usually only a few parts per million and even in the ozone layer it is only one part in 100,000.

The atmosphere can be split up into several regions from the surface to the fringes of space. The lowest part of the atmosphere, the troposphere, is where weather systems occur. Here the atmosphere is moist, generally gets colder with height, and is characterised by convection. The next region is the stratosphere, where temperatures increase with height, creating a stable, layered structure. Here the atmosphere is dry, and this is where the majority of the ozone lies. The boundary between these two regions is the tropopause, which in the Antarctic is at 10–12 km altitude. Above the stratosphere lie the mesosphere and thermosphere, with corresponding boundaries, the stratopause at around 45 km and the mesopause at 80 km.

Ozone concentrations at the surface were first measured reliably by Robert Strutt (later Fourth Lord Rayleigh) in 1918 using spectra of a hydrogen lamp recorded through 5 kilometres of air. These measurements showed that ozone concentration could not be uniform throughout the atmosphere, as a higher concentration was required to explain the sharp cutoff at around 300 nanometres (nm) seen in stellar spectra. Three years later, Fabry and Buisson used spectrographic techniques to demonstrate that its principal atmospheric location is in the stratosphere, though it was not until the 1930s that the actual vertical distribution was first measured. It was soon recognised that measuring the variation in the total ozone column was of meteorological interest, and Professor G. M. B. Dobson developed a prototype ozone spectrophotometer in the 1920s. His instrument is still the standard today, and around 120 Dobson spectrophotometers have been built.

Dobson's instrument measures ozone by comparing the intensities of two wavelengths of light from the sun, one of which is absorbed quite strongly by ozone, whilst the other is only weakly absorbed. The ratio of the intensities varies with the amount of ozone present in the atmosphere, and a well-calibrated instrument can measure ozone amounts to within a few percent. The instrument uses wavelengths between 305 and 340 nm, and these are selected by means of prisms and a series of slits. It was initially a photographic instrument, but photocells were introduced in the mid-1930s and a photomultiplier in 1946.

The sun emits radiation in all parts of the electromagnetic spectrum, roughly 7% in the ultraviolet between 200 and 400 nm, 41% in the visible between 400 and 760 nm, and 52% in the infrared. The ultraviolet part of the spectrum is further divided into UV-A, UV-B, and UV-C. UV-A lies between 315 and 400 nm and gives rise to a suntan and aging of the skin. UV-B lies between 280 and 315 nm and is the damaging part of the spectrum. UV-C, which is totally absorbed by the atmosphere before it can reach the ground, lies between 200 and 280 nm.

Ozone is created by the photochemical destruction of oxygen, which liberates a free oxygen atom that can then combine with an oxygen molecule to create ozone. A third molecule is required to take away excess energy. The dissociation requires ultraviolet light of wavelength shorter than 240 nm. Sidney Chapman gave the first description of the photochemistry in 1930:

$$O_2 + hf -> 2O$$

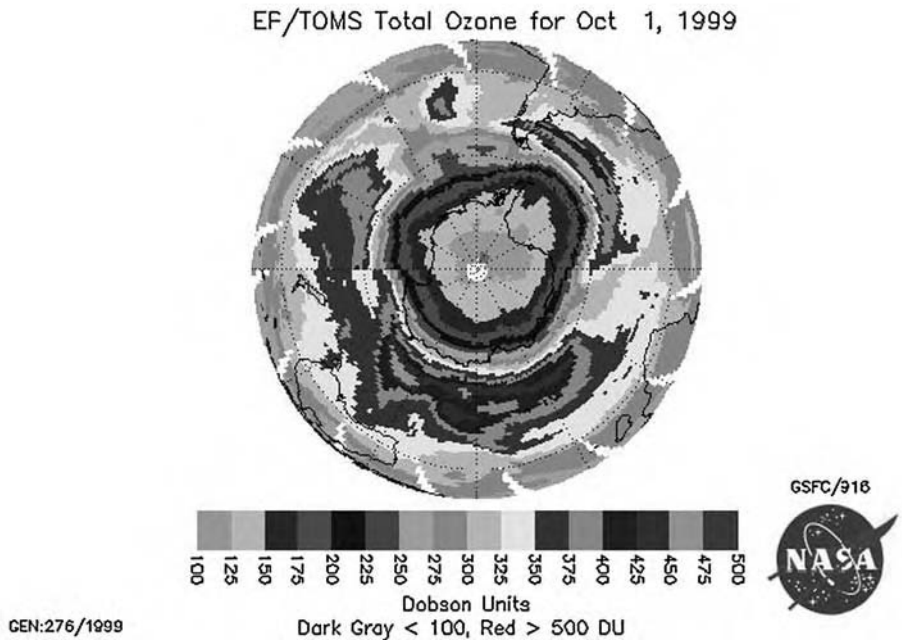
$$O_2 + O + M -> O_3 + M$$

Ozone can be dissociated by light of wavelength shorter than 1100 nm:

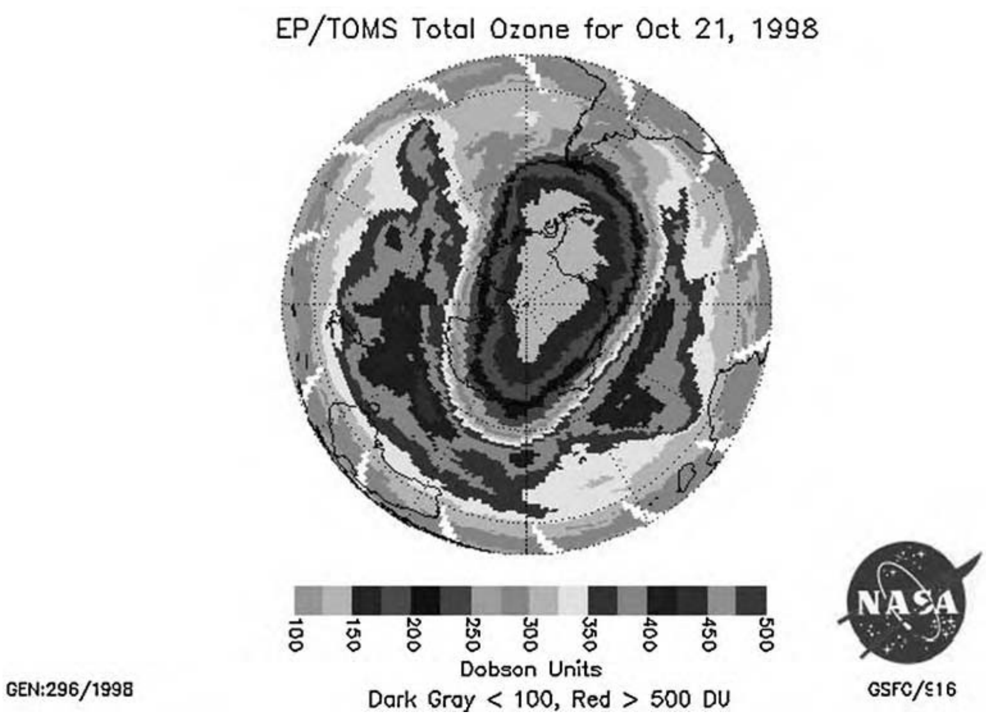
$$O_3 + hf -> O_2 + O$$

The free oxygen atom thus created quickly finds another oxygen molecule and the ozone is reformed with the net result of absorbing the solar radiation and inputting the energy into the atmosphere as thermal energy. The process is very efficient and virtually all radiation between 200 and 310 nm is absorbed, despite the relatively low concentration of ozone. The main ozone absorption bands in the ultraviolet are the Hartley (around 200–300 nm) and Huggins (around 300–350 nm), and there is the weak Chappuis band in the visible range (440–740 nm). In the lower stratosphere, below about 30 km, ozone has a long lifetime, and the ozone mixing ratio can be used to trace atmospheric motions.

A typical value for the total amount of ozone in a vertical column of our atmosphere is around 300 Dobson Units (DU), or 300 milli-atmosphere-centimetres, which corresponds to a layer of ozone 3 mm thick at



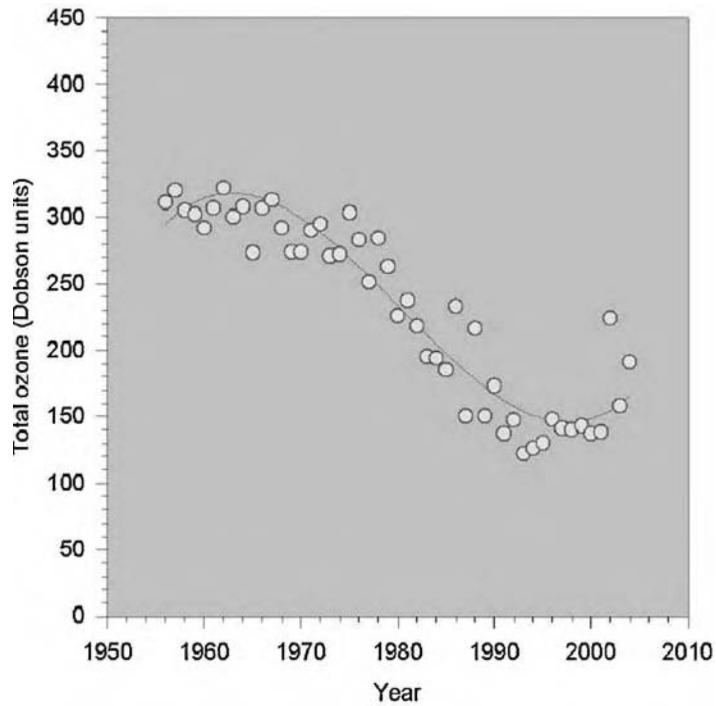
Satellite image showing the ozone hole in early October (1999). (From NASA/GSFC.)



Satellite image showing the ozone hole extending towards South America. (From NASA/GSFC.)

the Earth's surface. This 3 mm is in reality spread through the column, with the bulk of it lying in the stratosphere, with a maximum at around 17 to 25 km altitude depending on location.

Early studies of the ozone layer suggested a good correlation between changes in the total ozone column and synoptic-scale weather systems. The prospect of being able to use this in weather forecasting



Mean October ozone at Halley Station. (British Antarctic Survey.)

encouraged the setup of a global network of ozone monitoring stations; however, this was a blind alley. Developments in computer power have led to the use of numerical modelling as the key tool in weather prediction.

Day-to-day changes in ozone concentration are governed by motions in the stratosphere. These movements are a combination of horizontal and vertical transport. The ozone creation region above 50 km acts as a source or sink, so that descent of air acts to increase the total ozone column, whilst ascent of air acts to reduce it. Sustained ascent can lead to significant apparent ozone depletion and is responsible for some of the so-called mini ozone holes.

The longest-running ozone data set in the world is that from Arosa in Switzerland, going back to 1926. It shows a downward trend of a few percent per decade since 1970, with the depletion mostly occurring during the winter and spring. The Antarctic record is shorter, and in common with most Antarctic data sets begins in 1956 when stations began to be set up in Antarctica as part of the International Geophysical Year (IGY) of 1957–1958. Observing stations using the Dobson ozone spectrophotometer were set up at Argentine Islands (which later became Faraday and is now Vernadsky) and at Halley, and these have continued without interruption. In the 1960s, further measurements were begun at Amundsen-Scott, King Baudouin, Byrd, Hallett, and Syowa, although only the first and last of these continue today. In the 1970s, ozone measurements from polar orbiting satellites began, and a variety of satellites continue to make measurements. A few stations have made ozone profile measurements using chemical sondes, and this is also possible from ground-based measurements using the Umkehr technique.

The long record from Halley and its location within the winter polar vortex made it the best site for discovering what is now known as the Antarctic ozone hole (Farman, Gardiner, & Shanklin 1985). The seasonal pattern of the total ozone column in Antarctica is linked to the development and breakdown of the winter circumpolar vortex.

Historically ozone values were around 300 DU at the beginning of the winter (March in Antarctica), and similar at the end. During the winter, ozone amounts build up in a circumpolar belt just outside the vortex, due to transport of ozone from source regions in the tropics. Very high values, occasionally exceeding 500 DU, may be seen in this belt, which typically lies between about 60° S and 40° S. When the polar vortex breaks down in the spring (October), this belt of high-ozone column air sweeps across Antarctica, typically reaching the area around the central

Pacific sector first and the Atlantic sector last. Peak values used to exceed 450 DU, and then slowly declined back to 300 DU during the summer and autumn.

Since the mid-1970s, an increasingly different pattern of behaviour is seen—the Antarctic Ozone Hole. At the end of the winter, values are around 10% lower than they were in the 1970s and drop at around 1% per day to reach around 100 DU at the end of September. Values then slowly begin to recover, but the spring warming in the stratosphere is often delayed to the end of November or into December. Peak values in the spring warming are now substantially lower than in preozone hole times, and a decline in late spring and early summer values since about the early 1970s is very evident, as is the presence of very low October values since about the 1980s.

Ozone profiles can be measured using chemical sondes, which record the ozone concentration as the balloon rises through the atmosphere. The most frequent technique is to bubble air through a potassium iodide concentration cell, which generates a current that is proportional to the ozone concentration. These sonde profiles show that ozone concentration is low in the troposphere, but normally rises from the tropopause to reach a peak at around 17 to 22 km, thereafter falling. During the spring depletion, the majority of the loss occurs between 12 and 20 km altitude and virtually all ozone within this layer is destroyed. Although the peak ozone concentration is around 20 km altitude, the maximum absorption of short-wave solar radiation takes place at a much higher altitude of around 50 km. This absorption gives rise to the temperature maximum in the upper stratosphere.

The mechanism that controls the development of the Antarctic ozone hole is linked to the dynamics of the winter polar vortex. During the winter, lower stratospheric temperatures drop below –80°C, and at these temperatures stratospheric clouds can form. Observers at stations along the Antarctic Peninsula regularly see these clouds during the late winter as nacreous or mother-of-pearl clouds, created by lee-waves off the mountains of the Peninsula. More southerly stations sometimes report them as "ultra-cirrus," which may cover the entire sky in a faint milky veil. Occasionally there are reports of clouds that resemble noctilucent clouds, and it is just possible that such mesospheric clouds are seen in the Antarctic winter; these reports need further investigation. Once the clouds have formed, chemical reactions take place on the cloud surfaces, which together lock up nitrogen oxides and water and liberate chlorine and bromine (from CFCs, Halons, and other similar chemicals) in an active form. When exposed to sunlight, catalytic reactions take place, which rapidly destroy ozone. The simplest catalytic cycle that destroys ozone involves chlorine with chlorine monoxide (ClO) as an intermediary:

$$\mathrm{Cl} + \mathrm{O_3} \rightarrow \mathrm{ClO} + \mathrm{O_2}$$

$$\mathrm{ClO} + \mathrm{O} \rightarrow \mathrm{Cl} + \mathrm{O_2}$$

The same amount of chlorine is present at the beginning and end of the reaction and is the catalyst for the reaction to take place. Bromine can take part in similar cycles. More complex reactions also take place and together they can destroy ozone at around 1% a day until the catalytic cycle is broken, usually by other species reacting with the chlorine or chlorine monoxide to convert it into an inactive form. Paul Crutzen, Mario Molina, and Sherwood Rowland carried out pioneering work on these catalytic cycles in the 1970s, and in 1995 they received the Nobel Prize for their work.

Satellite images give a global picture and show the formation of the ozone hole within the strong winter polar stratospheric vortex. Globally, ozone amounts are generally lowest at the equator and highest at subpolar latitudes. The polar vortex acts as a barrier and hence, ozone-rich air builds up around it, in subpolar latitudes. Inside the vortex, ozone depletion is enhanced by chemical reactions on polar stratospheric clouds, which form in the very cold vortex. When the circumpolar vortex is at its strongest, the ozone hole tends to be roughly circular, but as it weakens, the vortex often becomes strongly elliptical and often offset from the Pole towards the Atlantic. At these times the northern edge of the vortex can reach as far north as 50° S in the Atlantic sector, posing a risk of increased UV exposure for the inhabitants of southern South America and the sub-Antarctic islands. The wave rotation period of the vortex is typically around a fortnight and this can be used to give rough forecasts of the period when such areas are most at risk. As the vortex warms, the clouds begin to disappear and chemical depletion ceases. With further warming the vortex begins to break down and the subpolar ozone-rich air sweeps across the continent.

The lower stratospheric temperature is strongly correlated with the total column ozone at any one location, a relationship first described by Reed and Normand in 1950. The mean 100 hPa temperature over Antarctica during October to December is now significantly lower than it was 30 years ago. This is due to a combination of the delayed spring warming and the lower amount of ozone in the stratosphere. The decrease in October ozone at Halley since the mid-1970s is very marked. This stratospheric change has potential implications for the surface climate, though the direct coupling between stratosphere and troposphere is weak.

The first signs of ozone depletion can, in retrospect, be seen from the mid-1970s, but the change did not become significant enough to be noticed until the early 1980s. Since then the ozone hole has grown deeper and lasts longer. In addition, the late-spring maximum has become much reduced and there are signs of depletion in the autumn. During the late 1990s, the maximum depth of the ozone hole stabilised, reflecting the nearly complete destruction of ozone in the vulnerable part of the atmosphere.

The size and depth of the ozone hole at its maximum extent now seem to be near their peak. The 2000 and 2003 ozone holes were the largest yet seen and reached an area of 28.4 million square kilometres. The ozone hole in 2002 was anomalous as a result of unusual stratospheric conditions and does not represent a recovery. The size of the hole is constrained by the circumpolar vortex, which in turn is constrained by the size of the Antarctic continent. The depth of the hole is constrained by the height range where temperatures are cold enough for the stratospheric clouds to form. A very slow return to the pre-1970 situation should be attained, provided that the Montreal Protocol is adhered to, and that there are no other changes to the atmosphere.

The Montreal Protocol is an international agreement that is designed to reduce the total chlorine and bromine load in the stratosphere. These gases largely reach the stratosphere in the form of CFCs and Halons, which were liberated in the troposphere from aerosol, refrigeration, foam-blowing, and fire-extinguishing systems. They have a typical stratospheric lifetime of 50 years, hence the expectation of a return to pre-1970 conditions on that timescale. The protocol was first drawn up in September 1987 and subsequent reviews have made it ever more stringent. The original agreement was to halve the use of CFCs by 1999, with the 1990 amendment agreeing to a complete ban by 2000. The developed world achieved the target well in advance of this date and production of other ozone-depleting chemicals will stop in the early years of this century. The developing countries were allowed a longer timescale to cease production and some took full advantage of this to continue production. This has delayed the timing of the maximum halogen loading of the atmosphere into the twenty-first century.

Other changes are, however, happening to the atmosphere, in particular the rising level of greenhouse gases. These act to warm the lower troposphere, but also act to cool the lower stratosphere. This may prolong the period when stratospheric clouds can form, and hence enhance ozone depletion. This may delay the recovery of the Antarctic ozone hole past the middle of the twenty-first century. It also raises the possibility of an Arctic ozone hole forming in the next 20 years. At present the northern polar vortex is relatively weak and usually breaks down in January or February, much earlier in the corresponding season than in the Antarctic. The combined effect of slowly declining ozone throughout the Northern Hemisphere and the increase in concentration of greenhouse gases is leading to a cooling of the Arctic stratosphere. The colder stratosphere and the increased temperature gradient between equator and pole increase the strength of the circumpolar vortex, making it more stable. Because it lasts longer, the spring warming is delayed, stratospheric clouds are present into the spring, and photochemistry rapidly destroys ozone.

Other short-lived events can also affect the ozone layer. Space shuttle launches briefly perturb the stratosphere, but their effect is soon past. Major volcanic eruptions, such as Mt. Pinatubo in the Philippines, which put several cubic kilometres of material into the stratosphere in 1991, can affect the ozone layer for a few years and can trigger depletion in parts of the layer that are not normally affected by the stratospheric clouds. The greatest Antarctic depletion yet seen occurred in 1992; however, turbidity measurements show that the material had largely dissipated by the mid-1990s. A major meteorite impact or atmospheric fireball, such as occurred over Siberia at Tunguska in 1908, could also damage the ozone layer.

All living cells contain DNA, a complex molecule that carries the genetic code, which describes the structure and biochemistry of the organism. UV can harm living things by damaging their DNA, which readily absorbs high-energy UV-B radiation. Many plants contain the pigment chlorophyll, which absorbs visible light as the energy source for photosynthesis. It also absorbs UV-B light and becomes bleached and nonfunctional. Living things must therefore protect themselves from UV-B. Many microbes, plants, and animals can synthesise protective pigments, for example, the brightly coloured lichens found encrusting rocks.

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See also **Amundsen-Scott Station; Clouds; International Geophysical Year; Polar Mesosphere; Synoptic-Scale Weather Systems, Fronts and Jets; Weather Forecasting**

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PACK ICE AND FAST ICE

Introduction

Sea ice is frozen sea water. Each year in March, following the brief Antarctic summer, the surface of the ocean around the Antarctic coast cools to the point of freezing. This occurs at a temperature of approximately –1.8°C, lower than the freezing point of fresh water because of the ocean's salinity. The first evidence of freezing is an unconsolidated layer of tiny ice crystals, called frazil ice, that give the surface an oily appearance. These crystals quickly coalesce to form a more consolidated cover that thickens as the air temperature drops, eventually creating a solid interface between the atmosphere and ocean.

Unlike the continental ice mass covering Antarctica, which has formed by millions of years of accumulated precipitation, most of the sea ice around Antarctica is less than 1 year old, waxing and waning on an annual cycle. At minimum extent in February, sea ice covers an area of approximately 4 million km^2. Then, at maximum extent in September, the sea ice cover has expanded to almost 20 million km^2, an area 1.5 times that of the Antarctic continent (13.2 million km^2), and slightly greater than the area of South America (17.8 million km^2). This annual change from open ocean to ice cover represents one of the greatest seasonal changes in physical properties anywhere on earth, and has an extraordinary influence on oceanic and atmospheric circulation and marine ecosystems.

Sea Ice Extent and Concentration

Since the early 1970s, satellite sensors have provided global, daily coverage of the sea ice zone in both hemispheres. The most reliable data on sea ice extent are from November 1978 through to the present, and over this period a slight increase in Antarctic sea ice extent has been reported. This is in stark contrast to the Arctic, where a significant decrease in summer sea ice extent over the past several decades has been observed. Regional changes in Antarctic sea ice extent have been reported, particularly in the peninsula region where there has been a sustained increase in air temperature over the past several decades, but these have not reflected a change in total extent because of compensating changes in other regions. These anomalies reflect, at least in part, teleconnections to lower-latitude climate phenomena such as the Southern Oscillation, and highlight the sensitivity of sea ice to anomalies in climate forcing. There is substantial evidence that year-to-year variations in sea ice cover in the Bellingshausen, Amundsen, and Ross Seas are linked to variations in surface air pressure, air temperature, and sea-surface temperature that occur during El Niño events. On much shorter time scales, the location of the sea ice edge is influenced by wind and ocean currents, and may move northward or southward by tens of kilometers per day under strong wind conditions. Over the longer term, however, the mean location of the ice edge reflects the location of the freezing isotherm, which is influenced by longer-term changes in oceanic and atmospheric temperature and circulation. The only sustained change observed in Antarctic sea ice extent is in the Peninsula region, where a decrease in mean air temperature of approximately 0.6°C per decade has been observed since 1950. Trends in sea ice extent may be linked to climate change, or to changes in oceanic and atmospheric circulation in the polar regions.

The sea ice extent varies not only seasonally but also from year to year and on much longer geological timescales. During the last glacial maximum, for example (i.e., the period 25,000 years ago when the average temperature of the earth was approximately 5°C cooler than at present), the sea ice around Antarctica in winter covered approximately twice the area of the Southern Ocean today. Evidence for this comes from diatom assemblages in deep-sea sediment cores, which are representative of ice-covered seas, and can be used to identify seasonality as well as total extent. The more northerly extent of sea ice would almost certainly have influenced the circulation pattern of the Southern Ocean at that time as well as the climate of the mid- and high-latitude regions. Another proxy for sea ice extent may be the amount of methanesulfonic acid (MSA) measured in glacial ice cores. MSA is an oxidation product of dimethylsulphide (DMS); it is produced by sea ice algae and may be found in higher concentrations in the atmosphere (and therefore glacial ice) during periods when sea ice extent is greater. This holds true for one area off East Antarctica dating back to 1841 and is currently under investigation in other areas around the continent.

Unlike the Arctic, which has an indigenous native population and is surrounded by countries with active military and economic interests in the sea ice zone, the Antarctic is far more isolated and has subsequently received far less attention. Captain James Cook, the first explorer to circumnavigate the Antarctic in 1773, was unable to penetrate far south of the sea ice edge, and wrote in his log book, "should anyone possess the resolution and fortitude to...[push] yet further south than I have done, I shall not envy him the fame of his discovery, but I make bold to declare that the world will derive no benefit from it." However, in the early 1900s expeditions by explorers including Douglas Mawson, Robert Falcon Scott, Roald Amundsen, and Ernest Shackleton did venture farther south, obtaining the earliest scientific discoveries from the Antarctic. Perhaps most famous is the drift track of Shackleton's ship *Endurance,* which provided some of the first information on the strength and drift patterns of Antarctic sea ice after it was trapped and subsequently crushed by ice in the Weddell Sea in 1915. Whalers and sealers, who were active in the Southern Ocean between the 1920s and 1950s, also kept logs of their encounters with sea ice, particularly the location of the ice edge, where blue, fin, and minke whales were commonly found. These records have also been used as a proxy for ice-edge location in the presatellite era; however, questions remain about the accuracy and consistency of the data, and their suitability for comparison with the modern satellite record.

The International Geophysical Year in 1957–1958 saw a significant increase in scientific activity in Antarctica, and the establishment of a number of national Antarctic research programs that are still active today. For the most part, however, sea ice was not a focus of Antarctic research at this time, and was primarily regarded either as a hindrance to shipping operations or a means of transport around the coast. It was not until the 1970s that research began to focus on the structure and properties of Antarctic sea ice and its role in the global climate system, with dedicated scientific expeditions to examine the sea ice environment. This coincided with the advent of satellite remote sensing, which provided complete daily coverage of the sea ice zone in both hemispheres, using a passive microwave radiometer. This instrument measures the "brightness temperature" (which is related to the physical temperature) of the earth's surface, enabling it to differentiate the colder ice and snow surfaces from relatively warm sea water. It has a distinct advantage over visible band imagery in that it can obtain data regardless of cloud conditions and darkness, although there are circumstances (particularly in summer, in regions of thin ice, and in coastal zones) when ambiguities arise. As well as being able to identify the location of the sea ice edge, passive microwave data are also very useful for determining the concentration, or compactness, of the sea ice cover. In most of the Antarctic, the sea ice zone is a complicated mixture of different ice types and open water, and the ice concentration (given as the percentage of a particular area covered by sea ice) may vary significantly on subdaily timescales. The passive microwave instrument has geophysical products that range from 12.5 to 25 km^2 on the ground, which means that the ice conditions are averaged over this area to provide a mean value. Other satellite sensors, each designed for a specific purpose, have different surface footprints and measure different surface properties, and may be affected differently by clouds, darkness, or other atmospheric conditions.

Antarctic Sea Ice Terminology

Most of the sea ice around Antarctica is known as "first-year" ice, having formed since the previous summer. First-year ice is regionally variable, but on average grows to approximately 0.5–1.0 m thick, significantly less than in the Arctic. In coastal regions the ice may become "landfast" and continue growing up to 1.5–2.0 m thick. Dynamic or mechanical processes play a far greater role in the development of the drifting pack ice north of the landfast ice zone. Pack ice floes often do not grow to more than a few tens of centimeters thick before being deformed by the action of wind, waves, ocean currents, and tides. The net result is a complicated mixture of different ice types, different ice thicknesses, and open water that is constantly in motion and changing in thickness and morphology. The processes of mechanical redistribution are called "rafting" and "ridging"; rafting describes the action of one floe riding up over another, effectively doubling the thickness of ice each time it occurs, while ridging describes the convergence of floes that buckle and break to form pressure ridges of ice blocks that may reach 10 m or more in thickness. The subsequent changes in surface and bottom topography cause increased drag with the ocean and atmosphere, and influence processes such as ice motion, snow accumulation, light penetration, and the mechanical strength of the ice.

The motion of sea ice is extremely complicated. It is primarily influenced by wind and ocean currents, but tides, the Coriolis force (the influence of the rotation of the earth), atmospheric pressure gradients, the tilt of the ocean surface, and internal ice stresses all play a part. On a large scale the ice cover can be regarded as a continuous medium, and most sea ice computer models treat it as a viscous–plastic material that behaves as a viscous fluid for small strain rates and flows in a plastic manner for large strain rates. Sea ice with high compactness will resist more compression and shearing than that with low compactness, and thick ice will resist deformation more than thin ice. Ice deformation may create open water areas between ice floes, where ocean–atmosphere heat exchange may be several orders of magnitude greater than through a consolidated ice cover, and where new ice often reforms. These areas are known as "leads" because of their suitability for navigation, and they provide access between the ocean and ice for wildlife. The new ice formed in leads can be crushed into ridges when the surrounding thicker floes converge, transforming thin ice into thick ice much more quickly than would occur simply by freezing. The prevalence of leads determines the ice "concentration," which is a measure of the ratio of ice cover to open water. During the ice growth season, leads facilitate new ice formation and increased ice mass, while in summer they absorb solar radiation, warming the surface layer of the ocean and contributing to ice decay.

Sea ice that survives the summer melt season is known as "second-year" ice, unless it survives more than one summer, in which case it is referred to as "multiyear" ice. The Weddell Sea, Bellingshausen/Amundsen Seas, and eastern Ross Sea are the areas where second-year ice is common around Antarctica. These are not only the southernmost waters around the coast, they are also areas where ocean circulation pushes ice toward the coast and causes it to pile up and thicken. Multiyear ice (surviving two or more summers) is found in limited quantities in the Antarctic; it is more common in the Arctic, where the sea ice cover is older and thicker and may survive for several decades. Surface melt can occur on the surface of multiyear floes in the Antarctic, creating widespread areas of slush. As a result, melt-water can percolate down to the surface of the sea ice and refreeze to form "superimposed ice," which is effectively a fresh ice layer.

Sea ice is further classified as either "pack" ice, which under the influence of wind and ocean currents may drift up to tens of kilometers per day, or "landfast" ice (commonly referred to simply as "fast" ice), which is attached to the coast and immobile. Fast ice is common in coastal bays and around grounded icebergs, where it typically grows to a uniform thickness of between 1 and 2 meters. Its maximum thickness is usually reached in September, and depends on the balance between the atmospheric and oceanic heat fluxes at the top and bottom surfaces of the ice, respectively. It creates an important transition between the Antarctic continent and the drifting pack ice, particularly for wildlife that use it as a breeding ground, or for a location to haul out of the water. Most fast ice is eventually broken up by waves, which penetrate to the coast once the pack ice to the north has melted. The fast ice floes then become an integral part of the pack ice, drifting and deforming with the wind, waves, and currents.

Sea Ice Drift

To measure sea ice drift and deformation, scientists use satellite-tracked drifting buoys that are placed on ice floes and monitored remotely. These provide regular (usually hourly) updates of their position and have shown average daily drift speeds in some areas of the Antarctic pack ice as high as 15–20 km/day. Around most of the continent the ice drift along the coast is towards the west, driven by the East Wind Drift. Further north the net drift is to the east as a result of the eastward-flowing Antarctic Circumpolar Current (ACC). Gyre circulations at various locations around the continent connect the eastward- and westward-flowing regimes, such as in the Weddell and Ross Seas, or where bottom topography diverts ocean currents toward the north or south. Drifting buoys are often also equipped with air temperature and pressure sensors that provide near-real-time data for weather forecasting models. These data are extremely valuable in data-sparse regions where there may be no other observations for distances of hundreds to thousands of kilometers.

The drift of sea ice contributes to the redistribution of fresh water around the Southern Ocean. First-year Antarctic sea ice has a salinity of about 6–8 parts per thousand (ppt), compared with seawater, which has a salinity of approximately 33 ppt. The salt that remains in the ice is trapped in tiny brine channels between ice crystals that are completely fresh, while the rest of the salt is deposited into the ocean. The subsequent drift of sea ice results in a net transport of freshwater away from the area of ice formation. This is particularly the case in some coastal features known as "polynyas," where sea ice growth rates are high but the ice is quickly advected away from the coast. Polynya is a Russian term, adopted as part of the common sea ice nomenclature, for an area of open water surrounded by ice. They can be up to several tens of thousands of square kilometers in size and are maintained by particularly cold katabatic (gravity-driven) winds that drain off the Antarctic continent. Total ice growth in the more active polynyas may be on the order of 10 meters per year, although the ice thickness in these polynyas at any one time is never more than a few centimeters.

Ocean–Sea Ice–Atmosphere Interaction

The salt deposited into the ocean as a result of sea ice formation drives a vertical circulation process between the surface and deeper layers of the ocean. Salt added at the surface by sea ice formation makes the surface water more dense, and therefore heavier, causing it to sink toward the bottom. There it may accumulate in depressions on the continental shelf and eventually spill over the sill, mixing with warmer, saltier water masses over the continental slope. This is a key process in the formation of Antarctic Bottom Water, and an important link in the ocean "conveyor belt" responsible for redistributing heat between the equator and the poles and maintaining our current climate system. The formation of Antarctic Bottom Water is known to occur only in the Weddell and Ross Seas, and off the Adélie Land coast, where the necessary combination of bathymetry, high ice production, and water mass mixing occurs. The properties of bottom water can be observed well north of the equator in the Atlantic and Pacific Oceans. The deeper waters being brought to the surface as part of the vertical convection beneath the ice are warmer and rich in nutrients, facilitating high biological productivity in the surface waters. This is enhanced during summer when sea ice melting has the dual effect of releasing algae into the water column and establishing a stable, low-salinity surface layer that inhibits mixing. Any change to this vertical circulation would therefore have serious implications for the Southern Ocean ecosystem.

Sea ice affects the interaction between the ocean and atmosphere in a number of other important and complex ways. For example, depending on its thickness and snow cover, sea ice can be up to an order of magnitude more reflective than the ocean; therefore, it reflects much more of the sun's incoming energy back into the atmosphere. This causes a "positive feedback" with the climate system, whereby the changed conditions that result from the formation of sea ice enhance the likelihood of more sea ice. That is, the surface becomes more reflective, therefore less heat is absorbed at the surface, and therefore more ice is likely to form. The reflectance (or albedo) of open water is 7% of the incoming radiation from the sun, compared to 49% for ice >70 cm thick. The addition of a 3-cm snow cover increases the albedo even more, up to 81% for ice >70 cm thick.

The accumulation of snow on sea ice also contributes to the redistribution of fresh water around the Southern Ocean. Precipitation that accumulates on an ice floe might only be deposited into the ocean when the ice melts, which could be hundreds to thousands of kilometers away, and many months later. Snow falling on sea ice also drives another important process in the Antarctic, which is the formation of "snow ice." This occurs when snow accumulates to the point where it overloads the sea ice and pushes the ice surface below sea level. Sea water then floods the base of the snow layer, creating slush, which subsequently refreezes to form an additional layer of ice between the sea ice and the snow. This new layer is called "snow ice" and can often only be identified separately from sea ice by measuring the ratio of ^{18}O to ^{16}O isotopes in the melted samples. The formation of snow ice is important because it increases the volume of ice present in the pack ice without having the same input of brine to the ocean that occurs when sea ice forms. Studies indicate that snow ice formation is prevalent in all areas of the Antarctic pack ice and therefore is an important consideration in mass balance studies of the sea ice zone.

Sea ice is thought to be intimately related to biological productivity in the marine ecosystem, providing a refuge for some animals and a platform for others. Microorganisms are trapped in the sea ice structure as it forms, often in higher concentrations than occur in the water column, and then released again when the sea ice melts. During their time within the ice environment, some species thrive while the growth of others is either inhibited or stopped completely. Gradients of temperature and salinity within the ice dictate the living conditions for organisms trapped there. The amount of snow cover will also largely dictate the amount of light available. Near the top of the ice, conditions will typically be colder, with a higher concentration of salt within the brine channels, while the bottom of the ice will be warmer with larger, less-saline pores in the ice. This may change in the summertime when the surfaces of floes become saturated with melt water and algal communities near the ice–snow interface flourish. When this happens, the organisms within the ice may become sufficiently concentrated that the ice turns brown, decreasing its albedo and resulting in more light absorption and enhanced melt. High concentrations of organisms also occur near the bottom of the ice and there is considerable evidence that krill utilize these communities for food, particularly during late winter. Krill is a key component of the food chain and a primary source of food for baleen whales and various species of seals, penguins, and other birds. Both adult krill and larvae have been observed feeding on the under-ice communities.

As well as reflecting incoming energy at its upper surface, sea ice also has an insulating effect on the ocean—an effect that is further enhanced by the addition of snow cover. Heat in the ocean, which would normally be given up to the atmosphere, therefore remains trapped within the upper layer of the ocean. This is an example of a "negative feedback" process, whereby heat trapped in the ocean as a result of sea ice formation may limit or prevent further ice growth.

Sea Ice Thickness

Measuring Antarctic sea ice thickness is a problem of great topical interest, as long-term changes in the sea ice thickness distribution are likely to be a sensitive indicator of global climate change. The sea ice thickness distribution is also an important input parameter to computer models of global climate, and is important for efficient planning of Antarctic shipping operations. Recent technological advances using satellite-based radar and laser altimetry offer some hope that satellite data may soon provide broad spatial coverage for sea ice thickness by converting measurements of freeboard (the height of the ice or snow surface above sea level) into total ice thickness by assuming bulk densities for the ice and snow cover. Until such satellite-based data are available it will be impossible to measure or monitor sea ice thickness on basin-wide scales. In the meantime, however, efforts continue using other technologies that have, to date, provided a valuable inventory of Antarctic sea ice thickness data. These range from sophisticated measurement devices such as upward-looking sonar (ULS) and electromagnetic (EM) techniques to simple drilled measurements and estimates of sea ice thickness from ships. While each technique has its merits, none provides the continuity of large-scale spatial measurements required for comprehensive sea ice thickness monitoring.

Upward-looking sonars are instruments moored below the ocean surface that measure sea ice draft by recording the response time of an acoustic signal transmitted by the instrument and reflected off the underside of the ice. The ice draft measurement is then used to determine ice thickness based on assumptions of the water column properties (which affect the speed of sound) and the ice and snow density. The instruments have been quite successful in some regions, but a high percentage of those deployed have never been recovered, as a result of either equipment failure or destruction by icebergs. Most instruments are moored at least 170 m below the surface to avoid iceberg hits; however, even at this depth they may still be destroyed by large icebergs that have a draft significantly greater than this. There are also significant unknowns that affect data processing, such as the snow cover on the ice, and seasonal changes in water column properties that cause seasonal changes in the speed of sound and the measured response of the instrument.

Electromagnetic techniques have been used extensively in both hemispheres. Until recently, their use in the Antarctic has been limited to ship-based surveys and thus has been limited to thinner ice areas accessible by ship. This problem has been overcome by the use of airborne EM systems, which can yield regional-scale estimates of sea ice thickness. The technique utilizes the large (2–3 orders of magnitude) contrast in electrical conductivity between sea ice and seawater. Consequently, the conductivity of the sea ice is negligible in comparison to the seawater conductivity, effectively making the ice transparent to a low-frequency EM field generated by the transmitter coil of an EM instrument. The instrument then measures the quadrature component of the secondary magnetic field, normalized by the primary field, which yields the height of the instrument above the ice–ocean interface. Sea ice thickness can then be calculated by subtracting the height of the instrument above the ice surface, which is typically measured using a laser. It is widely accepted that EM methods provide reliable estimates of the thickness of level sea ice; however, estimating sea ice thickness near three-dimensional structures such as pressure ridges is difficult because of the presence of conductive seawater or slush layers, and the smoothing of the observed response over the "footprint" of the instrument. Consequently there are regions and seasons when the technique is not suitable, and its use is limited to within flying range of coastal stations or research vessels in the sea ice zone.

Ice-thickness estimates from research (and other) vessels in the Antarctic have also yielded extremely valuable ice-thickness information in recent years. This technique relies on trained observers taking regular (usually hourly) estimates of sea ice conditions from the ship's bridge as it moves through the pack ice, and recording them in a common database. Observations of sea ice thickness are made as ice floes are broken and turned sideways along the hull of the ship, using a measuring stick or buoy of known diameter suspended close to the sea ice as a guide. More than twenty thousand such records of sea ice type thickness, floe size, and snow cover characteristics have now been compiled into a single database that provides valuable first-order estimates of these properties for the Antarctic. Additional information on sea ice topography is used to account for the mass of sea ice in ridges.

Field Studies and Future Work

Field studies in the Antarctic have also provided a great deal of information on the characteristics of sea ice. Experiments such as Ice Station Weddell in 1991 and Ice Station Polarstern in 2004/2005 have been dedicated experiments that have followed the evolution of a particular ice floe over a period of weeks to months. Experiments conducted at these drifting ice stations have yielded extremely valuable information on the seasonal changes in ice conditions, ice dynamics, and biogeochemistry of the sea ice zone. There have also been many other ship-based experiments and field sampling by different countries involved in Antarctic sea ice research. These include process studies that have focused on polynya processes, ice deformation using satellite-tracked drifting buoys, validation of remotely sensed data using field measurements, and the effect of sea ice formation on water mass modification. The collected data can provide insights into ice properties that help scientists to interpret satellite imagery, and can improve the way in which physical processes are parameterized in climate models. Sea ice core sampling is usually an integral part of any field experiment, and the data from these samples have collectively yielded information on regional and seasonal differences in the crystal structure and therefore the development of the sea ice. By examining thin sections of the ice cores between cross-polarized filters, it is possible to identify different ice types, such as frazil crystals, columnar ice crystals, snow ice, and superimposed ice, each of which indicates a different process of floe development.

In the future, monitoring changes in the properties of Antarctic sea ice will be of great importance. There is unequivocal evidence of change in the Arctic region, and some suggestion that similar change is occurring in the Antarctic Peninsula region. If the sea ice environment changes in the future, this may well be associated with changes in oceanic circulation and will undoubtedly influence the ecosystems of the Southern Ocean and the wildlife resident there. While field studies have yielded extremely valuable information on sea ice characteristics, and satellite data have provided a detailed record of ice extent and concentration since the 1970s, the Antarctic sea ice zone remains the most data-sparse region on earth. A great deal more data are needed to monitor this area for change; in particular, long time-series data on sea ice thickness are of key importance, but will only be available through improved satellite technology that is not currently available.

ANTHONY WORBY

See also **Antarctic Bottom Water; Antarctic Ice Sheet: Definitions and Description; Biodiversity, Marine; Circumpolar Current, Antarctic; Climate Change; Climate Modelling; Climate Oscillations; Continental Shelves and Slopes; Cook, James; Icebergs; Ice Core Analysis and Dating Techniques; International Geophysical Year; Marginal Ice Zone; Marine Biology: History and Evolution; Penguins: Overview; Polynyas and Leads in the Southern Ocean; Remote Sensing; Sea Ice: Microbial Communities and Primary Production; Sea Ice: Types and Formation; Sea Ice, Weather, and Climate; Seals: Overview; Sediments and Paleoceanography of the Southern Ocean; Southern Ocean: Climate Change and Variability; Surface Energy Balance;**

Surface Mass Balance; Thermohaline and Wind-Driven Circulations in the Southern Ocean; Wind; Zooplankton and Krill

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PALEOCLIMATOLOGY

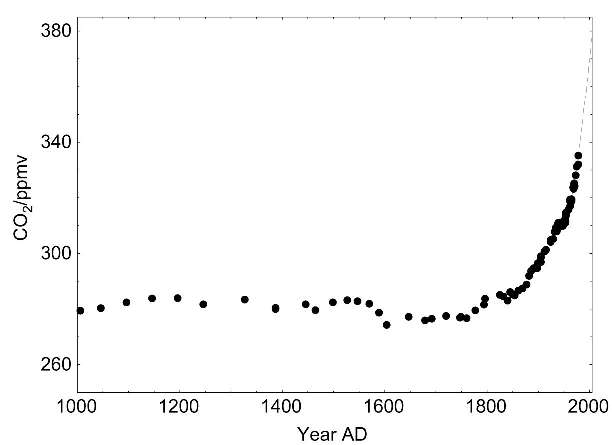
Paleoclimatology is the study of past climate. The climate of Antarctica over very long timescales can be studied in the geological record, and it reveals that the continent has not always been the cold place it is now. The ice sheet first appeared around 40 Ma, and the causes of this glaciation are the target of both data collection and modelling studies. However, most Antarctic paleoclimate studies cover a much shorter period, within the late Quaternary period (the Quaternary is approximately the last 2 million years). Although marine and lake sediment records are available, ice cores are at the centre of such studies, and now cover a period of over 800,000 years. They reveal that Antarctic climate has varied with a dominant period of 100,000 years, in concert with the ice ages and interglacial periods that dominated the climate of the northern hemisphere. However, ice cores also show that the major greenhouse gases, carbon dioxide (CO_2), and methane (CH_4), varied in a pattern similar to Antarctic climate, as did many other environmental parameters. In this way, the study of Antarctic paleoclimate actually contributes key datasets for our understanding of global climate change.

Paleoclimate Records

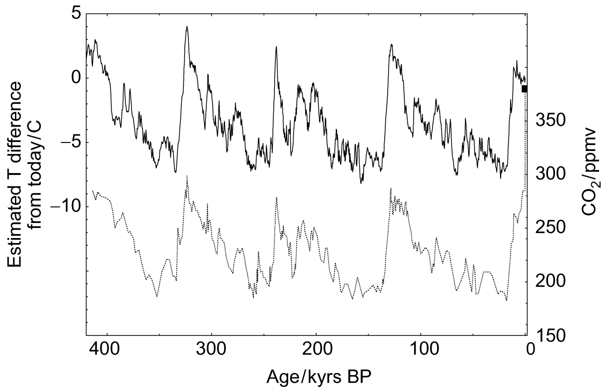
Past climate is documented mainly by making measurements of the physical, chemical, or biological properties of some type of sedimentary sequence. The main requirements are that the sequence be laid down in a monotonic order (so that the order of events is preserved) and that some property of the sequence be controlled by one of the environmental variables that we wish to know about (for example, temperature). Among the archives that can be used in various parts of the world are marine sediments, lake sediments, peat bogs, corals, ice cores, speleothems (stalagmites and stalactites), and tree rings. Over longer time periods, fossils found in sedimentary rocks can indicate the environment at a past time.

In Antarctica and the Southern Ocean, many of these archives are not available, and paleoclimate studies have been confined to ice cores, marine sediments, and lake sediments (as well as geological records for longer time spans). Lake sediments are mostly confined to the last few thousand years (partly because some records are obliterated by advancing ice from time to time). Marine sediments can span much longer periods, although nearshore records can also suffer from the effects of ice advances. Ice cores in Antarctica now span a period of over 800,000 years (800 kyr), although there are also numerous datasets that span only a few centuries.

Marine sediments consist of rock fragments and preserved biological remains that fall through the ocean column and are accumulated at the ocean floor. They can be recovered using shipboard corers

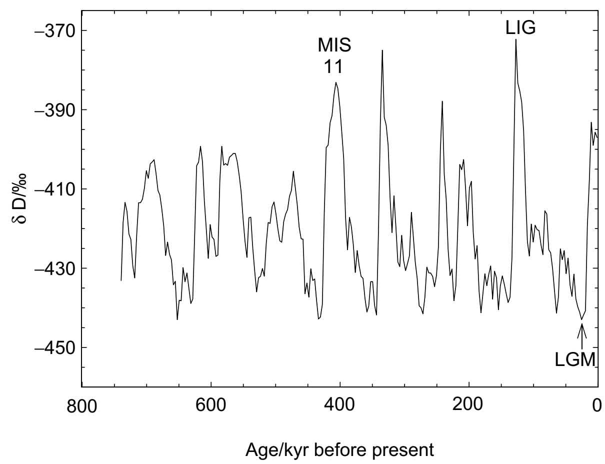


Atmospheric carbon dioxide from the Law Dome (Antarctica) ice core over the last millennium (Etheridge et al. 1996). Modern measurements in the atmosphere are shown as a line for the last 50 years, while the ice core data are shown as symbols.



Estimated temperature (based on deuterium values, solid curve, left axis), and carbon dioxide concentration (dashed curve, right axis) from the Vostok ice core, Antarctica, for the last 420,000 years (Petit et al. 1999). The current CO_2 concentration, based on atmospheric values measured at Mauna Loa, has been added as a symbol. The original deuterium data have been corrected to allow for the temperature of the source water (Vimeux et al. 2002).

that penetrate the sediments and return cylinders of mud to the surface. In the continental shelf regions of Antarctica, glacial debris is a particularly important part of the sedimentary record, and its study can indicate the style of glaciation and the timing of transitions between ice sheets, ice shelves, and open conditions. Elsewhere, assemblages of biota (for example, diatoms) can be identified as being associated with particular conditions (for example, sea-surface temperature values, or cover by sea ice). Sediments up to about 50,000 years old can be dated by radiocarbon dating methods, which involve measuring the ^{14}C content. Older sediments can often be dated by other radiometric methods.



The deuterium (representing temperature) record from the EPICA Dome C core covering the last 740 kyr (EPICA Community Members 2004). LGM: Last Glacial Maximum, LIG: Last Interglacial, MIS11: Marine Isotope Stage 11. The temperature difference between the LGM and the present is estimated as 9°C.

Lakes are rather rare in Antarctica, and confined to a few warmer parts of the continent and sub-Antarctic islands. The sediments at their bed can also be recovered by techniques similar to those for marine cores, with generally hand-held corers deployed from small boats or platforms, or from solid lake ice surfaces. They likewise contain sediments derived from surrounding surfaces, as well as biological material from the lake itself and from its catchment area. These can indicate, for example, the climatic conditions at the surface of the lake. In some cases, lakes can change from fresh to marine depending on relative sea level at a site, and these changes are recorded as changes in biota.

Most of Antarctica is covered in cold ice, permanently below 0°C, and ice cores can be collected from any such area. As snow builds up to form an ice sheet, it collects a record of (mainly) atmospheric conditions at the time. Ice cores are cylinders (typically 10 cm in diameter) of ice retrieved from the ice sheet. Drills are cylinders with metal cutting teeth on the end; the barrel is rotated to collect the core. For depths to about 20 m, hand drills are used. Beyond that, an electromechanical drill, consisting of a barrel on the end of a cable, must be used. In the deepest drills, lengths of up to 4 m are retrieved on each "drop" of the drill. By repeating this many times one can penetrate deep into the ice sheet. Because of the importance of ice cores in Antarctic paleoclimate, I will describe the formation of the ice-core record in more detail in a separate, later, section, but for now I note that ice cores can tell us about many parameters in the environment; the surface temperature, the greenhouse-gas content of the atmosphere, and the occurrence of explosive volcanism are three examples.

Antarctica over Geological Time

Before proceeding to the shorter timescale that is the main focus of this article, I will briefly summarise what we know about the long-term environment and climate history of Antarctica over many millions of years. Within the fossil record and offshore sediments of Antarctica, there is a history of the climate that Antarctica itself has experienced. Geologists can learn there about the breakup of the supercontinent of Gondwana. About 200 Ma, this supercontinent included South America, Africa, India, Australia, and

New Zealand, with what is now Antarctica at its centre. Gondwana broke up over a period of about 160 million years, with South America the last fragment to separate from Antarctica.

At times in this past Antarctica was a warm continent, supporting a rich flora and fauna. Fossil leaves and wood, dinosaurs, and even marsupial mammals have been found in the geologic record. The earth as a whole, and Antarctica in particular, seem to have been on a long overall cooling trajectory throughout the Cenozoic Era, the last 65 million years.

Sometime around 40 Ma, the warm "greenhouse world" really ended with the appearance of the first ice sheet on Antarctica. The history of the extent and persistence of this ice sheet is uncovered not only in Antarctic studies but also by looking at the history of past salinity that can be deduced from marine sediments around the world. When snow falls on Antarctica, it consists of freshwater taken from the ocean. This has various effects as successive snowfalls build up to form an ice sheet: it lowers sea level; it makes the remaining ocean more salty; and because there is less of the heavier isotope of oxygen in the snow than there is in ocean water, it changes the isotopic content of the ocean. By measuring the isotopic content of shells in marine sediments, this ice-sheet growth can be documented and the climate history of the last 65 million years summarised (Zachos et al. 2001).

According to this summary, small ice sheets were intermittently present in Antarctica from just after 40 Ma. This is about the time that the Tasmania-Antarctic Passage opened, although it is a matter of debate whether this is significant. Later, the Drake Passage opened, separating South America from Antarctica. Around 15 Ma, the East Antarctic ice sheet became persistent. The appearance and growth of the ice sheet are clearly related to an increased cooling of the Antarctic continent. There is debate about the exact causes of this cooling, with two favoured ideas, of which one or both may be important: (1) the opening of ocean gateways between Antarctica on the one hand and South America and Australia on the other hand led to the development of circumpolar ocean currents that isolated the continent from warm northern waters, and (2) decreasing levels of CO_2 from the high levels at the start of the Cenozoic likely caused a global cooling trend.

The oxygen isotope data only give an indication of how much ice there was in the world, but not where it was. They have been supplemented by evidence derived from sediment cores from the Antarctic continental margin. The most ambitious project (the Cape Roberts Project) was an international initiative that retrieved some 1500 m of strata from 3 cores in the western Ross Sea. The drilling took place from a platform on the sea ice. The cores encompassed the period from 34 to 17 Ma, and give further evidence of the extent of glaciation during this period. From 34 to 25 kyr, this sector of East Antarctica seems to have had tundra vegetation and a subpolar climate. From 24 to 17 Ma, there is evidence of more extensive grounded ice, and the sector seems to have been cooler.

Ice-sheet expansion in West Antarctica probably occurred some 6 Ma, and the appearance of the first ice sheets in the northern hemisphere continents around 2 Ma heralded the start of the Quaternary period. It is in the later part of this period that we pick up the story of the more detailed paleoclimate records found in Antarctica.

Ice Cores

The first deep ice core to bedrock was the 1390-m Camp Century (Greenland) core, completed in 1966. Two years later, bedrock was also reached at Byrd Station in West Antarctica, at 2164 m. Since then, a huge number of shallow cores and a handful of bedrock cores have been completed in both Greenland and Antarctica. Ice cores can be thought of as containing information in three different forms.

Firstly, the water molecules themselves contain climatic information. The isotopic signature of ice is formed by evaporation and condensation of water, starting over an ocean source and ending up during snowfall over an ice sheet. There are two stable isotopes of hydrogen (^1H and ^2H [or deuterium, D]), and three stable isotopes of oxygen (^{16}O, ^{18}O, and ^{17}O, although we will only be concerned with the first two of these). Thus, water consists mainly of $H_2{}^{16}O$, but with a small proportion of the heavier forms, HDO and $H_2{}^{18}O$. The lighter forms of water have a higher vapour pressure. As a result, air masses become increasingly depleted in the heavier isotopes as more water is removed from them, which occurs as they get colder. The result is that colder site temperatures lead to water that is more depleted in the heavier isotopes (this is expressed as departures from a standard in parts per thousand, and labelled as $\delta^{18}O$ or δD). In reality the processes are more complex than this simple explanation would suggest (Jouzel et al. 1997), but as a general rule, lower values of the two isotope ratios indicate a colder air temperature.

Aerosol particles, as well as some gases that can become attached to ice surfaces or enclosed in the ice structure, form the soluble and insoluble chemical content of the ice. They are either enclosed in falling snow or deposited dry to the snow surface. Components of this part of the ice-core record include terrestrial dust from other continents, sea salt, and volcanic sulfate. Because aerosol is relatively short-lived in the atmosphere, interpreting some of these species in terms of quantitative changes in aerosol source and transport is difficult, but on the other hand they contain regional information that can assist in deciphering patterns of atmospheric transport.

Finally, snow at the surface is compacted and metamorphosed, first into firn, and then (at a depth typically of 60–100 m) into solid ice. Air bubbles get trapped in the solid ice, and they contain samples of the ancient atmosphere, which can be analysed to give the concentrations of stable trace gases in past times. Of particular interest is the ability to measure the past atmospheric concentration of carbon dioxide and other greenhouse gases. These measurements are rather unique in that they are not "proxies," as are almost all other paeoclimatic signals—what is measured really is the concentration of the gas in a sample of old air. The air component of ice cores forms at depth. For this reason, the air enclosed just below the bubble close-off depth in central Antarctica is from the late twentieth century, but the ice (containing the climate record) at the same depth is hundreds or even thousands of years old (depending on how much snow falls each year). To determine any time lag between a climate change and a trace-gas change, this ice age–air age difference must be accounted for.

As a result of all these different signals, ice cores should contain information about past temperature, atmospheric transport, greenhouse gas concentrations, volcanic eruption frequencies, pollution, and numerous other parameters.

Ice cores covering shorter time periods, and at sites with high snow-accumulation rates, may be dated rather accurately by counting annual layers, using the winter–summer contrast in many properties of the cores. At the sites with the oldest ice, snow accumulation is very low, and annual layer counting is not possible. Here dating relies mainly on glaciological modelling, constrained by a number of fixed points derived from comparison with other records where absolute dating may have been possible.

Ice cores range from numerous very shallow (10 m) cores containing just a few years of snowfall at high resolution, up to the longest cores (Vostok [Petit et al. 1999], at 3623 m currently) and the oldest cores (currently estimated at 890,000 years [although only 740 kyr is published at the time of writing] at Dome C [EPICA Community Members 2004]). The very long cores require multinational, multi-institute efforts: for example, the Dome C core is one of two deep cores being drilled by the European Project for Ice Coring in Antarctica (EPICA) in East Antarctica; it has combined the scientific, drilling, and logistic input of ten nations.

Climatic Information of Recent Centuries from Antarctic Records

In most cases, instrumental records of climate in Antarctica extend back only a few decades, with very sparse and limited information before that. We therefore have to rely on paleoclimatic evidence for even recent centuries.

Numerous ice cores exist from across Antarctica that cover the last few centuries up to about 2000 years. A particular focus for producing such records has been the International Trans-Antarctic Scientific Expedition (ITASE), which in practice is a series of traverses in different parts of Antarctica, on which shallow cores have been collected. The ice core data are supplemented by a very few lake and marine records. In general, the ice core data show few significant changes in climate indicators over recent centuries, implying that Antarctic climate has been reasonably stable over this period. In this section, we highlight just two particular results from Antarctic records covering this period.

The first one is an Antarctic result with global significance. As already discussed, the air bubbles in ice cores retain a record of the past concentration of stable atmospheric gases. The major greenhouse gases (especially CO_2 and CH_4) have been measured routinely in the atmosphere only for a few decades, and we are entirely reliant on the direct measurements available in ice cores for our knowledge of what happened before that. Sites with very high snow-accumulation rates can give the highly resolved records needed for recent centuries: the Australian site of Law Dome has provided particularly important records of greenhouse-gas concentrations (e.g., Etheridge et al. 1996).

The ice-core records show that the year-2005 atmospheric concentration of CO_2 is about 380 ppmv (parts per million by volume) and is about 30% higher than the preindustrial value of about 280 ppmv. This value was stable to within 10 ppmv for the previous millennium before about AD 1830. For methane the situation is even starker, with a preindustrial value of 0.7 ppmv, less than half the present concentration of 1.75 ppmv. Thus, from these Antarctic measurements we have clear evidence that current concentrations of greenhouse gases are highly unusual, with (as it turns out) no analogue in at least the last 450 kyr. This is one aspect of the debate about climate change that is settled and beyond dispute.

The second issue that can be addressed is that of whether any change, perhaps due to human influence, can yet be seen in the Antarctic climate itself. In general, ice cores do not provide a clear answer to this question: the expected signal is small compared to the noise in the proxy used for temperature, and across most of Antarctica we already know that no clear change is so far seen in surface temperature from the instrumental records. One intriguing result from ice cores has been a suggestion that there has been a significant reduction in sea ice extent, at least in the Indian Ocean sector of East Antarctica, since the 1950s. This is based on a decrease in the concentration of methanesulfonic acid (MSA) in an ice core (Curran et al. 2003): production of this chemical, via biogenic emission and atmospheric oxidation, is believed to be indirectly related to the ice extent in winter. Much more work is needed before it can be established whether this change is widespread, and whether it is really related to a change in climate.

The one region in which a warming has certainly occurred over the last few decades is the Antarctic Peninsula. In this region, there is some sign that the temperature proxy (oxygen isotope ratio) is high in recent decades in some cores, but it is not yet clear how unusual this is in the context of previous millennia.

Climate of the Holocene: The Last Ten Thousand Years

The Holocene is the period since the end of the last glacial period; it is considered to have a rather stable and relatively warm climate in many, but not all, regions of the world. For this period, in the Antarctic we have ice core, lake sediment, and marine sediment datasets, as well as some information on past glacier retreat in portions of the continent.

Ice cores show that, on the East Antarctic plateau, the early Holocene, from about 11–9 kyr before present (BP), was warmer than the present (Masson et al. 2000). The remainder of the period shows no obvious and significant changes across most of the continent. It is clear that the much larger ice sheets of the last glacial maximum (about 21 kyr BP) were still retreating in the early Holocene, so coastal cores can show a more confusing picture.

A complex picture of Holocene climate comes from the Antarctic Peninsula region, where a wide range of evidence exists, although so far no long ice core has been drilled for this region. However, a marine core from Palmer Deep, on the west side of the Peninsula, shows a rather complete record of Holocene climate for this ocean region. The abundance of diatoms in the core suggests that the area underwent a mid-Holocene climatic optimum between around 8.7 and 4.4 kyr BP (Sjunneskog and Taylor 2002). The cold Neoglacial period that followed seems to be significantly earlier than that indicated by terrestrial records elsewhere in the Antarctic Peninsula, and it remains difficult to reconcile the dates of different climate events along the peninsula.

Innovative studies of marine and lake sediments show that ice shelves may have retreated to, or beyond, their present positions at times during the Holocene. In the northern Antarctic Peninsula, marine cores from areas that have recently been uncovered by retreating ice shelves show that a similar retreat happened probably about 4000 years ago. There is other evidence from this area of warmer conditions at this time, although dating control on the different signals is poor. Further south, evidence from around George VI Sound suggests that the ice shelf there was absent about 8000 years ago, suggesting that this region experienced conditions warmer than the present at that time. It is not yet clear how to synthesise all these findings into a story that explains the Holocene changes in climate in the Antarctic Peninsula in relation to the rest of the world and to the climate forcing factors.

Although this section has concentrated on the climate of Antarctica itself, ice cores have provided important information for global climate studies over this time period also. In particular, records of many of the factors that force climate are most easily obtained from ice cores. The changes in greenhouse gases over this time are again taken from ice cores: both the major gases show changes, with minima in the mid-Holocene for CH_4 and in the early Holocene for CO_2, but the changes are small in comparison to those that preceded this period. Ice cores can also provide data on past changes in volcanic sulfate (from spikes in sulfate concentration in ice cores), and in solar activity (based on fluxes of the cosmic-ray-produced ^{10}Be); both datasets are essential input for attempts to model natural climate change during this period.

Glacial-Interglacial Cycles: The Last Eight Hundred Thousand Years

Ice-core climate records from central Antarctica have become iconic, as standard records showing the major climate shifts of the late Quaternary period. The main features of the records are similar right across the continent, as shown by the similarities in their common period of the three longest records, the 420-kyr Vostok core (Petit et al. 1999), the 340-kyr record from Dome Fuji (Watanabe et al. 2003), and the (so far) 740-kyr ice core from Dome C (EPICA Community Members 2004).

The most obvious feature of the temperature (deuterium) record is that warm and cold periods recur with roughly a 100,000-year period. This is the familiar pattern of warm and cold also seen in climate and sea-level data recorded in marine and terrestrial records worldwide. The cold periods are the times when large ice sheets covered much of North America and northern Europe; in the coldest parts (glacial maxima) sea level was as much as 120 m lower than it currently is. The warm periods are known as interglacials. The ice-core record shows that central Antarctica was also much colder (by between 8°C and 10°C) in glacial maxima compared to interglacials. The record shows that generally, in the last four glacial cycles, long glacial periods gave way rapidly to relatively short, sharp interglacials that lasted for only 10–30 kyr of the 100-kyr period.

The new EPICA Dome C core shows that, although the 100-kyr pattern persists throughout the record, the amplitude of change was much less in the earlier period (before 450 kyr BP). Interglacials in that period were much less warm than the current one; however, they persisted for a larger proportion of each cycle.

The underlying cause of the 100-kyr cyclicity is believed to be changes in the shape of Earth's orbit around the Sun. Aspects of Earth's orbit change on timescales around 20 kyr, 40 kyr, and 100 kyr (Milankovitch cycles). The 100-kyr period is that of changes in the eccentricity of the orbit. However, it is not yet clear why the relatively small changes in the pattern of solar energy receipt implied by Milankovitch cycles (and by the 100-kyr cycle in particular) lead to such major changes in Earth's climate. Ice cores provide some clues to this, by showing how some of the amplifying features of climate behaved.

In particular, the Vostok core shows clearly that the greenhouse gases, CO_2 and CH_4, increase and decrease in close concert with Antarctic climate. The changes in CO_2 look particularly similar to those of Antarctic climate, probably because it is Southern Ocean processes that play the largest role in the transfer of CO_2 between the atmosphere and long-lived reservoirs in the deep ocean. In the most recent glacial cycles, the CO_2 concentration is typically 180 ppmv in full glacial conditions and 280 ppmv in interglacials (remember that the present-day concentration is much more—about 380 ppmv in the year 2005).

Other aspects of climate recorded in ice cores also change on glacial–interglacial timescales. Sea salt, possibly related to sea-ice extent, and micron-sized dust, probably related to climate in southern South America, are two examples.

Most terrestrial records from the Antarctic continent are extremely sparse for any period beyond the Holocene, although various lines of evidence, including glaciological modelling, suggest that the Antarctic ice sheet was considerably larger at the last glacial maximum (perhaps by about one-third in volume). The direct evidence comes from examples from cosmogenic exposure ages of rocks above the present snowline (the amount of cosmogenic isotopes depends on how long the rocks have been exposed to cosmic rays, and thus indicates when they were last covered in ice). Other evidence comes from survey evidence of glacial scour marks indicating the past extent of ice streams, and from marine sediments showing that open areas were previously ice covered. Some scientists believe that the West Antarctic ice sheet may have partially collapsed during the last interglacial some 120 kyr BP, but this remains controversial.

Marine cores can also extend through the period that the ice cores cover. Compilations of the last glacial maximum indicate that sea-ice extent in winter was about double that of today (Gersonde et al. 2005). Summer sea-surface temperatures appear to have been lower by as much as 4°C–5°C in parts of the sub-Antarctic zone of the Southern Ocean. A very limited number of marine cores from the Southern Ocean cover longer timespans, even as much as the entire Quaternary, but more are needed before we can get a good representative picture of either sea-surface temperatures or sea ice extent over the longer period.

The Importance of Antarctic Paleoclimate Records

While it is interesting to observe the evolution of Antarctica itself, I will finish this article by emphasising the importance of Antarctic climate records for understanding global climate. The late Quaternary ice-core records have become the standards to which other Southern Hemisphere data are keyed. From them, despite some difficulties in synchronisation of different records, we can see the relationship in time and space between Antarctic climate, Southern Ocean temperature, CO_2 concentration, and ice volume. By comparing Antarctic and Greenland ice-core records, we can see the phasing of Northern and Southern Hemisphere climate. In particular, during the last glacial period (and probably earlier ones), the north shows massive and rapid millennial-scale climate changes (Dansgaard-Oeschger events), which are seen only in very subdued form in the south. At the transition from the last glacial period to the Holocene, the south shows a rather gradual change, while the north has most of its temperature increase in very large steps, quite late in the transition. These contrasts are also giving clues about mechanisms of climate change, probably related to the partitioning of ocean heat transport.

The Antarctic records are also giving key data about climate forcings and feedbacks that must be used if we are to understand past climate. Since we cannot expect to accurately predict future climate until we can reproduce that of the past, this is rather vital knowledge.

ERIC WOLFF

See also **Antarctic Ice Sheet: Definitions and Description; Antarctic Peninsula; Atmospheric Gas Concentrations from Air Bubbles; Climate; Climate Change; Drake Passage, Opening of; Firn Compaction; Fossils, Plant; Gondwana; Ice Ages; Ice Chemistry; Ice Core Analysis and Dating Techniques; Isotopes in Ice; Plate Tectonics; Streams and Lakes; Volcanoes; Vostok Station**

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PALMER, NATHANIEL

American sealer Nathaniel Brown Palmer (born August 8, 1799, Stonington, Connecticut) became one of the first people to see Antarctica in 1820. He was preceded by two others earlier that year: Fabian von Bellingshausen (on January 27) and Edward Bransfield (on January 30).

Palmer, whose father was a shipyard owner in Stonington, went to sea at the age of 12. He first sailed to the Antarctic in 1819, as second mate on the brig *Hersilia* (James Sheffield, master), which operated in the newly discovered South Shetland Islands, the first US vessel known to have visited the archipelago. The voyage brought home 8868 skins of fur seals, spurring other New England ship owners to outfit sealing expeditions.

Palmer commanded the 47-foot (14.3-m) sloop *Hero* on another sealing voyage in 1820. Among *Hero*'s five-man crew was Peter Harvey, born in Philadelphia in 1789, one of the first black persons to reach the Antarctic. *Hero* sailed with four other Stonington vessels in a group led by Benjamin Pendleton. After arriving in the South Shetlands, Palmer took *Hero* southward to search for a better anchorage. He moored inside the flooded caldera of Deception Island—almost certainly the first to do so. On November 16, 1820, either from Deception's southeast coast or from *Hero*'s mainmast, Palmer is said to have sighted Trinity Island to the southeast and the Antarctic Peninsula beyond. The next day, he sailed to investigate, but heavy ice prevented him from making a landing. In January 1821, while searching for seal rookeries, Palmer took *Hero* along the western side of the Antarctic Peninsula as far south as Marguerite Bay.

Later that year, commanding the sloop *James Monroe,* Palmer was sealing in the South Shetlands as part of another Stonington fleet led by Pendleton. In company with British Captain George Powell of *Dove,* Palmer sailed east; together they discovered a large island of a new group on December 6, 1821. Because there were no seals to harvest, Palmer had little interest in the island, but Powell went ashore the next day and claimed it for the British crown, calling it Coronation Island, and the group "Powell's Group," now known as the South Orkney Islands.

Palmer made a final Antarctic voyage from 1829 to 1831, commanding the brig *Annawan* and sailing in company with his brother, Alexander S. Palmer, master of the schooner *Penguin,* in a voyage from Stonington led by Pendleton aboard the brig *Seraph*. The private sealing and exploration voyage was the first to earn sanction by the US government. It included the first American scientist to visit the Antarctic, physician and geologist James Eights, who published seven papers on his findings, including his discovery of fossil wood in the South Shetlands, the first fossil discovery in Antarctica.

"Captain Nat," as Palmer was widely known later in life, became wealthy as a ship designer, owner, and master, particularly of the Yankee clipper ships used in the China trade. He died in San Francisco, California, on June 21, 1877, the day after returning from a voyage to Asia.

JEFF RUBIN

See also **Antarctic Peninsula; Bellingshausen, Fabian von; Deception Island; Sealing, History of; South Orkney Islands; South Shetland Islands; South Shetland Islands, Discovery of**

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PARASITIC INSECTS: LICE AND FLEAS

Lice (order Phthiraptera) and fleas (order Siphonaptera) are the only two groups of parasitic insects known from the Antarctic continent. Lice are wingless and flat-bodied, living as permanent parasites on warm-blooded vertebrates and feeding on the host blood, skin products, or feathers. Three suborders of Phthiraptera are represented: the Anoplura or sucking lice, with five species (family Echinophthiriidae) living on seals; the Amblycera (family Menoponidae) and Ischnocera (family Philopteridae) or chewing lice, with more than sixty species in eighteen genera, living on birds such as penguins, albatrosses, petrels, and skuas. Phthiraptera is the insect order with the greatest number of species in Antarctica.

Being permanent parasites, the habitat of lice is the skin and the plumage or pelage of their hosts. Moreover, the geographical ranges of lice, with very few exceptions, match those of their hosts. However, each species of louse occupies a distinct ecological niche on the body of the host. In the case of bird lice, there is usually a stout "head and neck" louse species on each species of albatross, petrel, and skua, coexisting with elongate "wing" lice and round "body" lice. Each Antarctic seal species is parasitised by its own unique species of sucking louse, with most specimens located on the hind flippers, tail, ankle, and hip of the host. Seal lice have special morphological adaptations, such as a thick skin covered with large scales that trap host sebum, to withstand cold temperatures and long submersion periods.

Among bird lice, the most speciose genera in the Antarctic are *Austromenopon* Bedford, 1939, represented by ten species of body lice; *Austrogoniodes* Harrison, 1915, represented by seven species exclusively parasitic on penguins; *Quadraceps* Clay and Meinertzhagen, 1939, represented by six species of wing lice; and *Saemundssonia* Timmermann, 1936, with nine species of head and neck lice. The remaining fourteen genera contain from one to four species each. *Pseudonirmus* Mjöberg, 1910, is the only Antarctic-endemic genus and contains three species, each parasitic on a separate host species (Cape pigeon, snow petrel, and Antarctic petrel).

The order Siphonaptera is represented by a single endemic genus and species: *Glaciopsyllus antarcticus* Smit & Dunnet, 1962 (family Ceratophyllidae), the Antarctic flea, parasitic on three species of petrels. A study of the biology of *Glaciopsyllus antarcticus* associated with Antarctic fulmars (*Fulmarus glacialoides* [Smith]) showed that its life cycle is closely synchronised with the breeding of its host. Unremarkably in such a cold place, fleas need the warmth of the host bodies to reproduce. Eggs are laid by adult Antarctic fleas when the host is incubating its own eggs, and immature stages (larvae and pupae) only develop when the host's chicks appear. Adult fleas overfeed on the chicks to produce large quantities of blood faeces, on which the larvae feed to complete development and pupate, all within the host plumage. Unlike all other known fleas, the Antarctic flea is remarkable in that pupae remain on the host body and, although not yet proven, pupae and adults appear to overwinter on the host while the latter migrates during its nonbreeding period.

Ricardo Palma

See also **Albatrosses: Overview; Antarctic Petrel; Cape Petrel; Penguins: Overview; Petrels: Pterodroma and Procellaria; Seals: Overview; Skuas: Overview; Snow Petrel; Southern Fulmar**

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PARASITIC INSECTS: MITES AND TICKS

Mites (Acari or Acarina) are small arachnids (phylum Arthropoda), usually less than 0.7 mm in body length, that live freely or in association with other animals. In the Antarctic regions, they inhabit ice-free terrestrial or marine ecological systems, in which their functional role is often important. This is especially the case for decomposer mites (which feed on decaying matter or fungi); others are herbivorous (feeding on algae or lichens) or predacious (feeding on other mites or small invertebrates). One mite group, the ticks (Metastigmata), is entirely parasitic of vertebrates. Mites are among the relatively few animal groups represented in all three Antarctic geographical regions, the continental, the maritime (Peninsula and nearby islands), and the sub-Antarctic (near and outside the Polar Frontal Zone). In the physically harsh continental Antarctic habitats, mites constitute (along with collembolans) the highest taxonomic level of living organisms. No vertebrates feed in these habitats, which support other lower invertebrate groups, such as nematodes, tardigrades, rotifers, and amoebae. The mite diversity of continental and maritime Antarctica is expectedly low, and these regions respectively comprise 29 and 54 species, compared to the more than 450 known species for the sub-Antarctic. A single sub-Antarctic island (Marion Island) may support more than seventy mite species. While five mite orders (Mesostigmata, Metastigmata—ticks, Prostigmata, Oribatida, Astigmata) are represented in the Antarctic regions, only the Prostigmata and Oribatida are known from continental Antarctica.

Continental Antarctic mites occur on nunataks (rocky peaks that protrude through the ice sheet) in the higher latitudinal zones, or along the coastal regions of east Antarctica. Their habitat comprises rocks or gravel that support patches of moss, alga (such as *Prasiola*), or lichens (such as *Usnea* and *Umbilicaria*). All continental Antarctic mites are free-living and, with the exception of one predacious prostigmatid genus (*Coccorhagidia,* Rhagidiidae), herbivorous, and they feed on algal and or fungi elements. Given the isolation and extent of glaciation of the continent, the origin of continental Antarctic mites has been a question of much interest. The oribatid mites (five species) are thought to have originated when the continent was part of Gondwana and to have survived the effects of the Neogene glaciation. This suggestion stems from the endemism of the family Maudheimiidae (*Maudheimia,* four species), and the exclusive distribution of the genus *Antarcticola* (Ameronothridae, one species) on islands having a Gondwanan association (South Georgia, Îles Kerguelen). The distribution of each of the four *Maudheimia* species, in relation to their phylogeny (evolutionary history), suggests that speciation resulted from isolation of populations during glaciation of the continent. The Prostigmata (twenty-four species) are hypothesised as having colonised the continent subsequent to glaciation, considering that close relatives (from the same genus) are found on surrounding islands. The prostigmatid mite families found in the region are Eupodidae, Nanorchestidae, Penthalodidae, Tydeidae, and Rhagidiidae.

Detailed ecological studies on Antarctic mites have typically been restricted to Signy Island (maritime Antarctic), South Georgia, and Marion Island. Analogous to the climatic conditions, the habitat conditions of the Maritime Antarctic are intermediate of those for the continental Antarctic and sub-Antarctic. The sub-Antarctic embraces the best-developed terrestrial systems, comprising a variety of habitat types and consequently supporting a high mite-species diversity, including numerous predacious mites. The habitat types are broadly grouped under epilithic (dominated by mosses and lichens) and vegetative (dominated by ferns and angiosperms) biotopes. The former biotope constitutes inland rock and gravel fields, as well as coastal rocky shores. Community studies suggest that the epilithic biotope has served as a glacial refuge, from which the vegetative biotope has become recolonised. Evidence for this derives from the epilithic biotope's having a higher mite diversity and supporting mites with specific habitat requirements. This is especially well exemplified by the supralittoral zone (just above the intertidal zone) of many sub-Antarctic islands, which contains principal Antarctic mite genera, including *Parasitiphis* (Mesostigmata), *Neocalvolia, Algophagus* (Astigmata), *Halozetes,* and *Alaskozetes* (Oribatida). These usually inhabit the lichens *Turgidosculum* and *Caloplaca*.

The marine zone comprises two evolutionarily distinct mite groups, referred to as primary and secondary marine mites. Primary marine mites constitute a single family, the Halacaridae (Prostigmata), with more than fifty known coastal species in the Antarctic region. They show a complete transition to the marine environment by the capacity for aquatic respiration and continuous submersion. Secondary marine mites are confined to the intertidal zone, and those that show a partial marine transition by feeding on marine lichens or algae belong to the Ameronothridae (Oribatida: *Halozetes* [twelve species], *Alaskozetes, Podacarus*) or the Hyadesiidae (Astigmata: *Hyadesia, Neohyadesia*). Because of the occurrence of ameronothrid mites in marine, supralittoral, and terrestrial biotopes, which were differentially affected by glaciation, these mites have been fundamental to understanding the evolutionary (historical) ecology of sub-Antarctic island invertebrate faunas. Regarding other aquatic systems, the astigmatid mite genus *Algophagus* is important from an ecological and evolutionary perspective. While they primarily inhabit freshwater bodies, some species occur in supralittoral and terrestrial habitats.

The mechanisms whereby mites disperse and colonise in the Antarctic remain speculative. Aerial dispersal seemingly imposes a level of desiccative and thermal stress beyond the physiological capacity of mites. Bird transport or oceanic dispersal, especially by means of rafting (on seaweed, for example), is a more probable mechanism of dispersal between islands. The numerous Cosmopolitan and European (Boreal) mite species found on islands in the region (approximately seventy) is evidence of human introduction, and some mites (such as *Tyrophagus*) are typically present where there is human activity. Although no obvious ecological threats have arisen from mite introductions, the situation could change in the future.

Because of its relevance to understanding issues such as ecological conservation, global warming, and species introductions, research has focussed on free-living mites, rather than on mites that live in association with animals. Ticks (*Ixodes,* Metastigmata [four species]) and some mesostigmatid mites *(Rhinonyssus)* are common parasites of penguins and other seabirds. A variety of seabirds are home to feather mites, which complete their lifecycles on or in the feathers (thirty-seven species are known from the Antarctic regions; Astigmata). *Halarachne* mites (Mesostigmata) live in the nasal passages of elephant or leopard seals. At least two cases of phoresy (a mutual association that functions in mite dispersal) are known for the Antarctic. Of particular interest are the phoretic nymphs of *Psylloglyphus* (Winterschmidtiidae, Astigmata) and *Glycacarus* (Glycacaridae, Astigmata) that attach to the tergites of a flea *(Notopsylla),* which in turn parasitizes grey-headed or white-chinned petrels of the sub-Antarctic.

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See also **Decomposition; Gondwana; Insects; Kerguelen Islands (Îles Kerguelen); Parasitic Insects: Lice and Fleas; Polar Front; South Georgia**

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PELAGIC COMMUNITIES OF THE SOUTHERN OCEAN

Pelagic communities include animals and microalgae that spend at least a part of their life suspended or swimming within open-ocean or coastal waters. In the Antarctic, the definition also includes species that interact with pack ice or ice floes.

Over the ~35-million-year existence of the Southern Ocean, some animal groups have adapted to the icy and homogenously cold conditions to a greater extent than others. Particularly striking is the dominance, in some areas, of Antarctic krill *(Euphausia superba),* which belong to a group (the euphausiids) that make up only a minor component of pelagic communities in other ocean systems. In other less-coastal areas, copepods dominate numbers, and at depth, species of zooplankton. The pelagic fish, by contrast, are rather underrepresented in the Southern Ocean. Animals capable of exploiting krill, such as whales, seals, and penguins, have flourished in this environment as seen nowhere else.

The Southern Ocean is bounded to the north by the Polar Front and by the Antarctic continent to the south. It comprises 10% of the world's oceans and is predominantly very deep (3000–4000 m). It contains two major features that dominate the biology of its pelagic communities: (1) the Antarctic Circumpolar Current (ACC) and (2) the seasonal ice zone (SIZ). The ACC is the strongest oceanic current in the world since the lack of any continental barriers allows the wind to drive the flow continuously around the globe. The current flows from west to east (clockwise) and contains numerous water masses separated by a series of oceanic fronts. The water masses in the northern regions are generally ice free and mainly differ according to their temperatures, salinities, and levels of nutrients. The differing types and prevalence of ice cause further zonation to the south.

The marginal ice zone (MIZ) is the first type of ice encountered when leaving open waters. The MIZ is 100–200 km wide and consists of small ice floes broken up by swell. The location of the MIZ depends on the extent of the SIZ, which, at its maximum, covers almost 19 million km^2, some 8% of the southern hemisphere. The SIZ advances and retreats at a rapid rate (up to 1.6 km h^{-1}) over the course of the year, shrinking to just 5 million km^2 by the end of the summer. The high level of biological activity in these zones matches the dynamic physical nature of the MIZ and SIZ. By contrast, the permanent pack-ice zone, which is sandwiched between the SIZ and the Antarctic continent, changes little over time and supports very few pelagic communities.

All Antarctic food chains are ultimately fuelled by the development and growth of phytoplankton (microscopic single-celled algae) that accumulate at the ocean's surface or on surface-dwelling ice. Phytoplankton growth (primary production) depends on light to drive photosynthesis, and these organisms thrive when conditions in the water column stratify, preventing them from being mixed too deeply. This stratification may be caused either by the warming of surface waters, as observed in northern regions, or by the melting of ice, as occurs in the retreating SIZ. Phytoplankton also need sufficient nutrients and trace elements in order to grow. When all conditions are satisfied, phytoplankton taxa, such as diatoms, dinoflagellates, and *Phaeocystis antarctica,* are capable of forming large blooms. However, the lack of trace elements, particularly iron, results in primary production being constrained in many areas of the Southern Ocean. Smaller species (picophytoplankton and nanophytoplankton) dominate the relatively low levels of primary production in these areas.

The primary productivity regime of a region makes a large difference to the type of pelagic community that can prosper. Regions where phytoplankton blooms occur regularly often support populations of Antarctic krill and their predators. A large part of these blooms remain unconsumed and the dying cells frequently form aggregates *(marine snow)* that descend rapidly. When this occurs in the open ocean, it provides food for deep-living pelagic organisms; in coastal waters, benthic communities will often consume it. In regions of low primary productivity, small organisms such as dinoflagellates and foramaniferans consume the dominant picoplankton and nanoplankton. These in turn are eaten by copepods (e.g., *Oithona*) that have small enough filters to capture them, or pteropods (Thecosomata) and salps *(Salpa thompsoni),* which use a mucus trap for the same purpose. Salps reproduce asexually and attain large levels of biomass when conditions are favourable. Although not strictly gelatinous (they consist of a transparent cellulose cuticle with an internal filtering chamber and muscles), they are considered to have low nutritional value and are rarely found in the diets of large predators. Their major consumer is probably *Themisto gaudichaudii,* a hyperiid amphipod that is much smaller ($\sim$20 mm long) than the salp itself ($\sim$60 mm). *T. gaudichaudii* is found in the diets of some large vertebrates.

The open ocean is a homogenous environment devoid of protective structures such as reefs. However, vulnerable pelagic organisms can use other strategies to reduce their risk of being eaten. Krill and *T. gaudichaudii* form large swarms in which individuals can forewarn each other of the advance of predators. Other organisms change their vertical location in the water column over daily or seasonal cycles. This is because most food items (particularly phytoplankton) are located in the sunlit surface layers where the risk of being detected by visual predators is the greatest. Visiting these layers only during the nighttime, or during limited times of the year, reduces this risk.

Although the vertical migration range of pelagic organisms such as krill, salps, and *T. gaudichaudii* remains within the epipelagic zone (0–250 m), other species start their journey from the mesopelagic zone (250–1000 m). These include the lanternfish (myctophids) and hatchetfish (argyropelecids), which are adorned with numerous photophores (light organs) that can be both a camouflage and a means of communication. Animals in the bathypelagic zone (1000–3000 m) do not make a daily journey to the surface but feed either on marine snow or on each other. Such animals are mainly jellyfish (such as comb-jellies and siphonophores), shrimps (penaeids and carids), and bioluminescent fish. Other organisms, such as the copepod *Calanoides acutus,* enter this zone during the wintertime in a state of diapause and so rely on their reserves of body fat to keep them alive until they ascend the following spring. Very few organisms are found in the deepest layers (the abyssopelagic zone, >3000 m) although shrimp-like crustaceans called mysids become relatively abundant at the interface with the sea floor (the benthopelagic zone).

Humans have exploited several animal groups in the Southern Ocean pelagic community over the past two centuries, including Antarctic fur seals *(Arctocephalus gazelle),* baleen whales (e.g., the Antarctic blue whale, *Balaenoptera musculus;* the fin whale, *Balaenoptera physalus;* and the humpback whale, *Megaptera novaeangliae*), toothed whales (the sperm whale, *Physeter macrocephalus*), icefish *(Champsocephalus gunnari),* Patagonian toothfish *(Dissostichus eleginoides),* and krill. With the exception of krill, the populations of each species were lowered to levels that threatened their extinction. This also upset the balance of other species within the ecosystem. Laws (1977) proposed that the near extinction of baleen whales in the early part of the twentieth century meant that 150 million tons of surplus krill became available for other predators such as crabeater seals *(Lobodon carcinophagus)* and penguins like the Adélie *(Pygoscelis adelie)* and macaroni *(Eudyptes chrysolophus)*. Many of these species increased in abundance over the mid-twentieth century. Since the moratorium on whale hunting was enforced in 1986, the populations of some whale species are thought to have recovered at a rate of 10% per annum while a simultaneous decrease in the population sizes of penguins and seals has been reported.

Meanwhile, krill populations have gone through periods of high and low abundance over the course of the twentieth century. Some say that the high levels of biomass reported earlier in the century were a result of the species moving towards its carrying capacity as the level of whale predation fell. The gradual decline in krill numbers since then is a result of, initially, the increase in the numbers of seals and penguins exploiting the krill surplus and, subsequently, the recovery of the whale population. However, others have proposed that the recent decline in krill numbers has been caused by the partial demise of their major habitat, the SIZ. Krill-rich areas, such as the Antarctic Peninsula, have recently undergone rapid warming and the extent of the SIZ has decreased in this region. Ice is particularly important to krill larvae, especially over winter, where it provides a refuge and source of food (ice algae). Krill also rely on blooms that occur at the retreating ice edge during the summer to fuel reproduction. The decline in krill has been accompanied by a simultaneous increase in the numbers of salps, which prefer open waters without blooms. Climate models able to predict the future extent of the SIZ in the Southern Ocean are still in their infancy and still have considerable error margins. However, it is likely that any further decrease will make this region less habitable for krill and less sustainable for large populations of their vertebrate predators.

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See also **Adélie Penguin; Antarctic Fur Seal; Blue Whale; Circumpolar Current, Antarctic; Copepods; Crabeater Seal; Fin Whale; Fish: Overview; Food Web, Marine; Macaroni Penguin; Phytoplankton; Polar Front; Polar Front, Marine Biology of; Southern Right Whale; Zooplankton and Krill**

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PENGUINS: OVERVIEW

Penguins are marine flightless birds, different enough from all other birds to merit an order (Sphenisciformes) of their own. Within the order are eighteen extant species and approximately forty fossil species, all similar enough in size, shape, and ecology to be included in the single family Spheniscidae.

Distinguished on land by their stocky build, upright stance, and narrow flippers, modern penguins are found almost exclusively in the Southern Hemisphere. Contrary to popular belief, they are not predominantly polar or even subpolar birds. They are found along cool and warm temperate coasts of South America, South Africa, Australia, and New Zealand and on the cool temperate islands of the Southern Ocean and the Antarctic and sub-Antarctic islands. The most northerly breeding population occurs on the Galapagos Islands, where a few individuals live north of the Equator. The genera and species are distinguished by their size, shapes of bill, and colour patterns of head and neck. The largest (emperor penguin) weigh some thirty times more than the smallest (little penguin).

All known fossils occur within the geographical ranges of modern species. In age, the species range from late Palaeocene or early Eocene (50–60 million years) to Miocene (5–10 million years). Most are represented by single tarso-metatarsi (ankle) or humerus (upper forelimb) bones, or fragmented skulls; in relatively few have even partial skeletons been identified. Measurements of these bones indicate that most fossil species lay within the size range of modern penguins. A few were much larger, standing up to 1.6 m (5 ft) tall and weighing up to 80 kg (176 lb). At least one species was notably smaller, standing only 33 cm (13 in) tall.

In skeletons and musculature, penguins show ample evidence of having evolved from flying birds, though the earliest known representatives of the family were already flightless. Once committed to swimming and diving, they were able to diversify in size; among modern penguins, the smallest feed mainly in surface waters, while the largest appear to be the deepest divers. Their evolution from relatively small flying birds, possibly akin to petrels and similar in size to the smallest modern auks, occurred in warm seas, before the presence of an Antarctic ice cap chilled the Southern Hemisphere. Only during and after the Pliocene period (2–3 Ma) were some of the southernmost species likely to have encountered icy seas. However, the insulation (overall feathering and subdermal fat) required to keep swimming and diving birds warm in temperate seas was a useful preadaptation for colder conditions. Currently the greatest concentrations of penguin species occur in cool temperate waters: New Zealand and its southern islands alone support seven breeding species, the Falkland Islands five species. The Antarctic region, including the continent and islands within the Polar Front (the northern limit of Antarctic surface waters), also supports five species, of which three (emperor, Adélie, and chinstrap) breed only south of the Polar Front.

The penguin body is almost completely feather covered, with only a narrow naked brood patch on the lower abdomen present during the breeding season. Tropical Humboldt, Galapagos, and African penguins have conspicuous bare patches on the face, possibly to shed surplus heat. All species are counter shaded (i.e., they have dark feathers on the head and back, white underneath). Newly grown dorsal feathers are black or dark brown, with a blue or grey spot that in some species (king and little penguins)

Species	Body Length, cm (in)	Mean Body Mass, kg (lbs)	Geographical Range
Emperor, *Aptenodytes forsteri*	115 (45)	30.0 (65)	Antarctica, including the Antarctic Peninsula
King, *Aptenodytes patagonicus*	94 (37)	15.0 (33)	Macquarie I., Prince Edward Is., Heard I., Îles Kerguelen, Îles Crozet, Falkland Is., South Georgia, South Sandwich Is.
Adélie, *Pygoscelis adeliae*	71 (28)	5.0 (11)	Antarctica, Antarctic Peninsula, South Shetland Is., South Orkney Is., South Sandwich Is., Bouvetøya, Peter I Øy, Balleny Is, Scott I.
Chinstrap, *Pygoscelis antarctica*	69 (27)	4.5 (10)	Antarctic Peninsula, South Shetland Is., South Orkney Is., South Sandwich Is., Bouvetøya, Peter I Øy, South Georgia, Balleny Is.
Gentoo, *Pygoscelis papua*	76 (30)	5.9 (13)	Antarctic Peninsula, South Shetland Is., South Orkney Is., South Sandwich Is., South Georgia, Falkland Is., Heard I., Macquarie I., Prince Edward Is., Îles Kerguelen, Îles Crozet,
Yellow-eyed, *Megadyptes antipodes*	66 (26)	5.4 (12)	Southeastern New Zealand, Campbell I., Auckland Is.
African, *Spheniscus demersus*	71 (28)	2.7 (6)	Southern Africa
Magellanic, *Spheniscus magellanicus*	71 (28)	5.0 (11)	Southern South America, Falkland Is.
Humboldt, *Spheniscus humboldti*	66 (26)	4.1 (9)	Northern Chile, Peru
Galapagos, *Spheniscus mendiculus*	53 (21)	2.3 (5)	Galapagos Is.
Fiordland, *Eudyptes pachyrhynchus*	56 (22)	3.6 (8)	Southwestern New Zealand
Erect-crested, *Eudyptes sclateri*	66 (26)	4.5 (10)	Antipodes Is., Bounty Is.
Macaroni, *Eudyptes chrysolophus*	71 (28)	4.5 (10)	Southern South America, Antarctic Peninsula, Falkland Is., South Shetland Is., South Orkney Is., South Sandwich Is., South Georgia, Prince Edward Is., Îles Crozet, Îles Kerguelen, Heard I., McDonald I., Bouvetøya
Rockhopper, *Eudyptes chrysocome* (three subspecies)	56 (22)	2.7 (6)	Tristan da Cunha, Gough I., Falkland Is., Tierra del Fuego, Prince Edward Is., Îles Kerguelen, Îles Crozet, Heard I., Île St. Paul, Îles Amsterdam, Macquarie I., Campbell I., Auckland Is., Antipodes Is., Bounty I.
Snares, *Eudyptes robustus*	53 (21)	3.0 (6.5)	Snares Is.
Royal, *Eudyptes schlegeli*	61 (24)	4.5 (10)	Macquarie I.
Little blue, *Eudyptula minor*	41 (16)	1.1 (2.5)	Southern coasts of Australia, New Zealand
White-flippered, *Eudyptula albosignata*	41 (16)	1.4 (3)	Banks Peninsula and Motunau I., New Zealand.

Figures are based on Stonehouse (1967) and Williams (1995). Body masses of all species vary widely according to breeding condition, gender, moult, etc. "Standing height" can be estimated as roughly 90% of body length.

dominates to provide an overall impression of silver-grey. After several months, the feather tips erode, darkening the dorsal plumage overall. Ventral feathers are white in most species, but emperors and kings are markedly yellow-to-gold on the upper abdomen, chest, and throat, merging into conspicuous yellow or golden-orange auricular patches. *Eudyptes* penguins have species-specific gold or yellow crests above the eyes; *Megadyptes* penguins have a bright-yellow coronet encircling the head. *Spheniscus* penguins carry distinctive black bands encircling the chest and throat. Bill colour varies from black to bright orange; in kings and emperors vivid coral or lilac plates line the lower mandible.

Individual body feathers on the midback and abdomen grow at a density of about 11 per cm^2 and range in length from 2 cm in the smallest species to 4.5 cm in emperor penguins. In all species, they are curved and flattened to overlap like roof tiles. Body feathers include aftershafts of down, which mat together to form a dense underlayer. Body feathers can be raised or lowered. When raised, the feathers part and permit air to circulate; when lowered they form an effective windproof and waterproof covering. Flippers are covered with tiny scale-like feathers; tail feathers in most species are short and stiff. Penguins spend much of their time ashore preening, oiling the feathers from a preen gland above the tail. All species undergo an annual moult, in which all the feathers are replaced simultaneously over a period of 2 to 3 weeks.

Additional insulation is provided by a layer of subdermal fat, barely present in warm-climate species and thickest in polar penguins. On the back and abdomen of emperors at the start of winter it may be 2.5 cm thick; on Adélies it may be up to 2 cm (0.8 in). On calm days in winter or early spring, with air temperatures around –40°C, snow may settle on the surface of an emperor or Adélie penguin. Despite the bird's high core temperature (c. 38°C), fat and feathers combine to ensure that very little heat escapes through the surface. Penguins are indeed so well insulated that, when active, they require radiating surfaces to shed heat to the environment. This function appears to be undertaken by the flippers, which are relatively uninsulated yet well supplied with blood vessels. Their white undersurfaces often appear pink (i.e., flushed with blood) in birds emerging from the sea. The bare faces of *Spheniscus* penguins may similarly act as radiators.

Most penguins are likely to spend the majority of their lives in the sea, emerging onto land (or sea ice) only to rest, preen, moult, and breed. *Eudyptes* penguins undergo long distance dispersions between breeding seasons, requiring them to spend at least 6 months continuously at sea. Penguins float low in the water, using flippers for propulsion and steering, with feet and tail combining to form a rudder. Underwater, the flippers are extended and appear to vibrate, moving the birds forward at speeds of 60–100 m per min. They feed exclusively in the sea, on a range of foods including planktonic crustaceans, fish, and squid. Swimming and diving abilities enable them to feed at depths below those of most flying birds. The smallest penguins (little and rockhoppers) feed almost entirely on plankton within a few metres of the surface. Those of intermediate size (gentoos, chinstraps, macaronis) dive to depths of as much as 100 m and can stay submerged for 3–5 minutes. The largest penguins (emperors, kings) dive regularly to 50–100 m in search of larger fish and squid. Emperor penguins have been recorded diving to 500 m, on hunting forays lasting more than 15 minutes.

Though sometimes described as clumsy on land, penguins can move fast over a variety of surfaces. Small and intermediate-sized species emerge through heavy surf to land on rocky shores or beaches, running, hopping, and if necessary climbing steep slopes to reach their nest sites. The larger species are less agile: kings land only on beaches, emperors almost exclusively on sea ice, both avoiding steep slopes. Species that encounter soft snow toboggan on their bellies, propelling themselves with toes and flippers. In early spring, Adélie and emperor penguins may have to walk 70–80 km over sea ice to reach their breeding grounds; gentoo and chinstrap penguins may scramble through snow to nest in colonies over 150 m above sea level.

Most penguin species nest in dense colonies, on beaches or cliffs within a few hundred metres of the sea. The largest colonies, for example of *Pygoscelis* penguins, may include hundreds of thousands of nests. Yellow-eyed and Galapagos penguins, by contrast, breed in solitary pairs, or in small groups of nests, well spaced apart. Like most other warm-climate penguins, they nest under cover of vegetation or in caves. *Spheniscus* and *Eudyptula* penguins typically nest in burrows. All but two of the known emperor penguin colonies form on sea ice; the others are on land.

Polar and subpolar penguins breed once yearly, returning *en masse* to their traditional colonies in early spring, and nesting, laying, incubating, and rearing their chicks simultaneously during the brief summer. Subtropical and tropical species are less tightly coordinated, and with breeding seasons that may extend throughout the year. Emperors and kings lay a single white egg that they incubate on their feet, warmed by a fold of abdominal skin. All other species lay two (rarely three) eggs, chalky white or bluish, which they incubate in nests made of pebbles, moss, and the bones of their predecessors. *Eudyptes* penguins lay one smaller egg that they usually discard, followed by a larger one that they incubate to full term. In emperors, only the males incubate, for a total of 64 days. In all other species, incubation is shared, for periods ranging from 54 days in kings to 33–36 days in the smaller species. Both parents brood and feed their young, bringing food and regurgitating it to their own offspring, which they find and identify by calling. Growing chicks are covered in dense woolly down, which they moult into juvenile plumage before leaving the nesting grounds. Those of the smaller species are ready for the sea some 7 to 9 weeks after hatching.

Chicks of emperor and king penguins, taking longer to rear, require anomalous breeding cycles. Emperors lay in mid-winter so that their chicks, which take 20 or more weeks to grow, are ready for the sea by mid-summer. Kings lay over an extended period in spring and summer, then retain their chicks in the colonies throughout the subsequent winter, when the chances of their survival at sea would be much reduced. King chicks may thus be a year old on first entering the sea.

Predators on land include skuas (*Catharacta* spp.); southern giant petrels *(Macronectes giganteus)* and leopard seals *(Hydrurga leptonyx)* are predators at sea.

BERNARD STONEHOUSE

See also **Adélie Penguin; Amsterdam Island (Île Amsterdam); Antarctic Peninsula; Auckland Islands; Birds: Diving Physiology; Bouvetøya; Campbell Islands; Chinstrap Penguin; Crested Penguins; Crozet Islands (Îles Crozet); Emperor Penguin; Fish: Overview; Gentoo Penguin; Gough Island; Heard Island and McDonald Islands; Kerguelen Islands (Îles Kerguelen); King Penguin; Leopard Seal; Macaroni Penguin; Macquarie Island; Polar Front; Prince Edward Islands; St. Paul Island (Île St. Paul); Skuas: Overview; South Georgia; South Orkney Islands; South Sandwich Islands; South Shetland Islands; Southern Giant Petrel; Squid; Zooplankton and Krill**

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PETER I ØY

Peter I Øy (Island) lies in the Bellingshausen Sea only 280 miles (450 km) off the Antarctic coast at 68°50′ S, 90°35′ W. Shaped approximately like an egg, its area of 60 square miles (156 km^2) is 95% glaciated, with a 131-ft- (40-m-) high ice wall or, in parts, steep cliffs, plunging into the sea. The island has volcanic origins and the highest peak, Lars Christensentoppen at 5381 ft (1640 m) asl, is an extinct and ice-capped volcanic crater.

The climate is hard, with strong winds, low temperatures, and snow. For much of the year thick pack ice encircles the island, making landing very difficult. On the west coast the rocky promontory Kapp Ingrid Christensen divides the bays Norvegiabukta and Sandefjordbukta with their narrow (c. 4-m-wide) strips of beach, and most landings occur here.

The vegetation is dominated by specialised hardy mosses and lichens. A few seabirds, particularly several hundred pairs of southern fulmars *(Fulmarus glacialoides),* nest in the cliffs, and small Adélie and chinstrap penguin rookeries exist on Framnesodden. Large numbers of seals, particularly crabeater and leopard, inhabit both the shore and particularly the surrounding waters.

Peter I Øy was first sighted in January 1821 by Thaddeus von Bellingshausen, commanding the *Vostok* and *Mirnyy,* and was named after Czar Peter the Great (1672–1725). However, pack ice prevented approach nearer than c. 16 miles (25 km). Ninety years later the island's existence was confirmed when Jean Charcot in *Pourquoi Pas?* sailed to within 3 miles (5 km). In 1926–1927, a Norwegian expedition led by Eyvind Tofte on the *Odd I* circumnavigated and surveyed the island without managing to land. Finally, the Norwegian second *Norvegia* expedition, captained by Nils Larsen and led by Dr. Ola Olstad, made the first landing on February 2, 1929. With a ceremony on Framnesodden in Sandefjordbukta, the island was claimed for Norway. Surveying work was done and a small hut built to house a depot for a future expedition. This was probably destroyed very quickly by the elements, although it is listed as no. 25 on the Antarctic Treaty Historic Sites and Monuments List. Larsen revisited in 1931 on *Norvegia,* but was unable to land. In May 1931, a Norwegian Royal Proclamation announced that the island was placed under Norwegian sovereignty, and in March 1933 it was declared a Norwegian dependency. In 1935, when a royal resolution was passed to prohibit sealing on Bouvetøya, Peter I Øy was included as a similarly protected area.

A second landing was made at the same spot in February 1948 by a Norwegian expedition on the *Brategg,* captained by Nils Larsen. Scientific investigations were carried out for 3 days until ice forced them to leave. A new hut was erected and a copy of the occupation document from 1929 placed inside. Again the hut was probably soon destroyed. Since then, sporadic landings have been made by various nations, mostly for short scientific investigations, and there have been a few tourist visits since 1980. In January 1987, five Norwegian scientists spent 11 days at the island for extensive investigations and surveying.

SUSAN BARR

See also **Adélie Penguin; Bellingshausen, Fabian von; Bellingshausen Sea, Oceanography of; Bouvetøya; Charcot, Jean-Baptiste; Chinstrap Penguin; Crabeater Seal; Leopard Seal; Petrels: Pterodroma and Procellaria**

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PETERMANN, AUGUST

The German cartographer and publicist August Petermann (b. Bleicherode, April 16, 1822, d. Gotha, September 25, 1878) had an important role as a promoter of the geographical exploration of Africa and the polar regions. The popularization of his conceptions of the physical geography of the Arctic Ocean encouraged European countries to take an active part in the exploration of the polar seas in the second half of the nineteenth century (Tammiksaar et al. 1999). Although Petermann had no ambition to be involved in the organization of the exploration of the southern polar regions, he had indirect, but considerable, influence on it, most notably due to his compilation in 1863 of the first special map of the physical geography of the Antarctic (Petermann 1863a). This was based on only the scanty observation data available.

Petermann's career as a scientist (1839–1845) started with taking part in the compilation of *Physikalischer Atlas* (1837–1848) with the cartographer Heinrich Berghaus. This provided geographical information in a novel way—on thematic maps. In 1845–1848, in Edinburgh, Petermann helped Alexander Keith Johnston, geographer to the Queen, to compile the English version of *Physikalischer Atlas* (1848) of Berghaus. After that (1847–1854), Petermann worked as an independent cartographer in London and became known as a promoter of geographical investigation in Africa. In 1854, he moved to Gotha in Germany and founded the geographical journal *Mittheilungen aus Justus Perthes' Geographischer Anstalt über wichtige neue Erforschungen auf dem Gesammtgebiete der Gerographie,* which quickly became the leading geographical journal in the world. The key to the success of the journal lay in the expeditious publication of the most recent geographical information and the use of it in maps (Wichmann 1888; Weller 1911). This made Petermann an influential man. He used his authority to promote the investigation of little-studied regions and to disseminate his geographical hypotheses.

In addition to the journal, Petermann was active in compiling atlases (for example, the highly valued *Stieler Handatlas*). He began to construct maps of the Arctic in order to depict the entire Russian Empire. His first innovative map in conical projection, entitled "Süd-Polar-Karte," was published in the *Stieler Handatlas* of 1863 (Petermann 1863a). A similar projection enabled him to delineate the routes of all known expeditions in the region of the Antarctic Circle without large deviations, by using the data collected on the border of drift and pack ice and hypothetical land sights. On the basis of the diverse data obtained and published on his maps, Petermann determined that the name "Antarctic continent" was used too frequently in Mercator projection maps, as the connecting of pack ice, ice walls, and observed lands with a line did not necessarily indicate the existence of a continent surrounding the South Pole (Petermann 1863b).

Although there were very few reliable observation data available on the Antarctic, Petermann concluded that the border of drift ice was changeable and varied regionally and yearly by approximately 1000 miles (1610 km). Despite the temperature isotherm of the Antarctic water discovered by James Clark Ross, he believed that the physical-geographical border of the Antarctic waters was constant and coincided with the northernmost border of drift ice at 55° S. This, according to Petermann, was the key to helping explain the movement of currents in the Antarctic, which in summer carried the drift ice to much farther north latitudes. Comparing these data and the air temperatures recorded in the Arctic and Antarctic, Petermann determined that due to the cold summers in the Antarctic—in contrast to the warm summers in the Arctic—there could not be a continent in the region of the South Pole, as continents accumulate warmth. According to Petermann, the cold summer and lack of living organisms in the Antarctic indicated that there was an ocean covering most of the area; he further believed that, having passed the drift-ice belt on a steamer, one could discover new lands and reach the South Pole (Petermann 1863b).

Petermann's conception of the physical geography of the Antarctic seems bizarre today, but in the 1860s—when scientists had not unanimously accepted or rejected the theory of continental freezing, had not yet been to the inner regions of Greenland, and had not yet investigated its ice cap—Petermann's hypothesis was considered feasible by many individuals who interpreted the numerous theories (often proceeding from the scientific knowledge of the eighteenth century) supposedly supported by the scanty factual data on the Antarctic. Alexander von Humboldt and Georg von Neumayer, for example, agreed with parts of Petermann's theory that an extensive Antarctic Ocean existed, and the instructions to the First German South Polar Expedition (1901–1903) even included the task of crossing the hypothetical Antarctic

Ocean. As often happens in science, the observations carried out during this expedition not only did not confirm the presence of the Antarctic Ocean, but helped establish just the opposite, the presence of an Antarctic continent under the continental ice.

ERKI TAMMIKSAAR

See also **Antarctic: Definitions and Boundaries; British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); History of Antarctic Science; Neumayer, Georg von; Ross, James Clark**

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PETRELS: PTERODROMA AND PROCELLARIA

The birds discussed in this article are in the order Procellariiformes and family Procellariidae.

Kerguelen Petrel *(Lugensa brevirostris)*

This is an ancient species of petrel, possibly 40 million years old, from which the fulmarine petrels evidently descended, and perhaps with an ancestral connection to shearwaters. It is uniformly slate grey with paler undersides of the primary feathers and inner leading edge of the underwing, a narrow black bill, and pale purplish-grey feet. It is large-headed and about 35 cm long with a mass of about 350 g. It flies with a characteristic swift flight, often towering high above the sea. Nonmigratory and normally restricted to Antarctic and sub-Antarctic seas, it reaches the edge of pack ice apparently circumpolarly, but ranges to 30° to 40° S in winter–spring, this northern limit associated with mortalities mainly of young birds on southern coasts (South Africa, Australia, New Zealand) after storms. Total populations have never been counted but may exceed 1 million and, apart from decreases on a few islands infested with rats *Rattus* spp. and feral cats *Felis catus,* seem relatively stable. Breeding sites are restricted to sub-Antarctic islands in the Atlantic Ocean (Gough and Inaccessible) and Indian Ocean (Prince Edward Islands, Îles Crozet, and Îles Archipelagos), but it disperses to the South Pacific Ocean.

Kerguelen Petrels visit their colonies nocturnally, breeding in 1- to 3-m-long burrows, usually in waterlogged habitat, which avoids competition with most other burrowing petrels. The nest is built up with mud and vegetation. Breeding occurs in spring–summer with pairing and mating in September, the single white egg laid in October, and hatching in December after about 49 days of incubation by both parents in long shifts. The chick is left unguarded from 2–3 days old while both parents range widely at sea but there is no data on their foraging ranges. After 60 days of rearing, the chick departs in late January to February. After breeding, the adults disperse to moult at sea but nonbreeders, which have been visiting through the summer, visit the colonies intermittently throughout the nonbreeding season of March to August. These petrels are relatively silent at colonies but occasionally utter sharp, wheezy, three-syllabled calls in flight. Nothing is known of their longevity, presumed to be some decades, or of their social structure, presumed to be in long-lasting, monogamous pair bonds. Their burrows are widely dispersed within colonies and they are solitary at sea, typically not following ships.

Large, red, mesopelagic crustaceans (decapods, amphipods, and mysids) are a major component of their diet, with tunicates possibly secondary, and mesopelagic squid and fish as minor items, indicating that much of their feeding may be at night. Their large eyes would assist such nocturnal feeding. They do not dive but catch their prey at the surface, sometimes associating with smaller toothed whales.

Mottled Petrel *(Pterodroma inexpectata)*

Similar in size to the Kerguelen Petrel at 35 cm long and a mass of about 325 g, this gadfly petrel is grey above with a transverse M-mark formed by the blackish outer primaries, greater upperwing coverts, and lower back. The crown and tail tip are darker grey, and there is a black eye patch. Underparts are white but for the brownish-grey belly, and a prominent black underwing stripe along the leading edge inwards to the wrist and then diagonally inwards almost to the axillaries. The stubby bill is black and the feet flesh-coloured with blackish extremities.

This species is endemic to New Zealand, but ranges widely in Antarctic seas, reaching the pack ice from 70° E to 75° W during summer months (December to March). Many if not all of these Antarctic foragers may be immature or nonbreeding. Its breeding grounds formerly included many colonies in hills and mountains of the North and South Islands, but human exploitation followed by depredations by introduced predators led to the extirpation of all colonies. It now breeds only in southern New Zealand in Fiordland, on islands around Stewart Island and at Snares Islands, where populations are now stable. The largest colony on Whenua Hou (Codfish I) has 1–2 million birds and is increasing after removal of predacious Weka *(Gallirallus australis)* and rats. After breeding, the whole population migrates to the North Pacific Ocean, reaching Alaskan seas and the Bering Sea. It is found in the North Pacific Ocean from late February to early November, with some remaining there through the northern winter.

Breeders return to their colonies in October to November, visiting nocturnally and nesting in 1- to 2-m-long burrows in quite dense colonies under tussock grassland, scrub, or low forest, sometimes alongside Sooty Shearwaters *(Puffinus griseus)*. Their habit of visiting colonies abundantly on wet nights led to the name Rainbird. The single white egg is laid in December to early January; it hatches mainly in February and the fledgling departs after about 90–105 days, rearing in May to early June. There are long incubation spells by both parents and absences of many days at sea finding food for their chick. Nonbreeders visit the colonies from November to early March and are very vocal in flight, uttering a complex variety of calls.

The diet of breeding birds is dominated by mesopelagic fish, particularly lanternfish of more than ten species, supplemented by small cephalopods and a few crustaceans. There are few Antarctic species among these prey, so the birds seen in Antarctic seas in summer, which feed mainly on squids, fish, and euphausiids, are presumably nonbreeders. They feed solitarily by surface-seizing, probably mainly at night, and sometimes associate with shearwaters *Puffinus* spp. when feeding. They ignore ships, usually being seen flying swiftly past.

White-Headed Petrel *(Pterodroma lessonii)*

The largest gadfly petrel, 45 cm long and about 600 g in body mass, its upper parts are grey from crown to tail with blackish wings and lower back. Head and nape become white as the plumage wears. There is a black eye patch. The underparts are white contrasting with the dark grey underwings. The bill is stout and black, and the feet are pale pink with black distal third of webs and toes. This species ranges circumpolarly in Antarctic and subantarctic seas from its breeding colonies on Possession Island (Crozet group), Kerguelen Archipelago, Macquarie, Auckland, and Antipodes Islands. It is an abundant species, although introduced predators have caused population decreases on Crozet, Kerguelen, Macquarie, and Campbell Islands (possibly extirpated). This petrel is nonmigratory, but range to the edge of the Antarctic pack ice, keeping south of about 45° S during the summer breeding season but reaching to 30°–35° S in winter, when longitudinal dispersal from the colonies is much greater. Its breeding grounds are at lower altitudes (0–300 m above sea level) and usually in tussock grassland on slopes or in dry, peaty herbfields.

Birds visit land nocturnally only, and nest in 1-2-m-long dry burrows. The breeding grounds are deserted for only 2 months of the year. Breeding birds begin to arrive back in August and, after mating, seem to have a long prelaying exodus, but its length is unknown. The single, white egg is laid from late November to December; it hatches after 55–60 days, and the chick is left alone after 3 days. The chick departs after about 102 days in May to early June, its parents also departing then or some days earlier, and the breeding grounds are deserted by late June. Nonbreeders also visit the colonies from about October to May and are responsible for most of the aerial calling, which comprises a variety of repetitive, sharp calls and softer cooing notes. Brown (sub-Antarctic) skuas *(Catharacta lonnbergi)* prey upon these petrels at nearly all of their colonies.

Little is known of the species' longevity, breeding age, and social structure, but, like other gadfly petrels, birds probably live potentially over 30 years, begin breeding at about 6 years, and form long-lasting, monogamous pair bonds. The burrows are quite dispersed within colonies and it is solitary at sea. Though slightly attracted to ships, it does not usually follow in their wake.

The diet of this petrel has been little studied, but mesopelagic cephalopods and crustaceans (mysids, amphipods, and decapods) are evidently important, and some lanternfish are also taken. They feed by seizing prey at the surface, detecting it while in flight, and do not dive. Most feeding may be at night. They loosely associate with prions *Pachyptila* spp. and shearwaters *Puffinus* spp. when feeding.

Soft-Plumaged Petrel *(Pterodroma mollis)*

Individuals are 35 cm long and weigh 300 g, somewhat like a small white-headed petrel; the two species belong in the same group within the genus. It is slate grey above with a blackish M-mark across outer primaries, greater upper-wing coverts, and lower back, and a grey tail. There is a black eye patch and the underparts are white but for a grey collar and dark grey underwings. The bill is black and the feet flesh-coloured with blackish extremities. There is a rare, entirely dark grey morph.

This is a nonmigratory, predominantly sub-Antarctic species but it encroaches into Antarctic seas in the South Atlantic Ocean, particularly in the Weddell Sea to 60° S in summer months. In the Indian Ocean, birds range mainly north of their colonies in sub-Antarctic and sub-Tropical seas. This is a very abundant species, with breeding colonies at Gough Island, Tristan da Cunha, Prince Edward, Îles Crozet, Îles Kerguelen, Île Amsterdam, and the Antipodes Islands. It is scarce in the South Pacific Ocean, but is increasing at the Antipodes Islands. Breeding takes place from September to June, with the single egg laid in 1- to 2-m-long dry burrows mainly in December, hatching in February, and the fledgling leaving in May to June. Colonies, which can be quite dense under tussock grassland and fernfield, are deserted only in July–August, with nonbreeders active there from October to June. The diet is dominated by mesopelagic crustaceans (decapods, amphipods, and mysids), with squid, fish, and offal also eaten. They feed by surface-seizing, are solitary at sea, and do not follow ships.

Grey Petrel *(Procellaria cinerea)*

This is a large petrel, 50 cm long and weighing about 1.1 kg, and it belongs to a group of petrels anciently related to shearwaters. It is grey above, the contour feathers edged paler, the crown, wings, and tail appearing darker, and the plumage browning slightly with wear. The underparts are white except for the dark-grey underwings. The bill is greenish-yellow with black on top; the feet are flesh-coloured with darker outer sides and yellowish webs. Its flight is strong and direct; more shearwater-like than that of its black relatives. It is circumpolar, breeding at Tristan da Cunha and Gough Island, and at the Prince Edward, Crozet, Kerguelen, Campbell, and Antipodes archipelagos. It ranges into Antarctic seas, farthest south in January to June to 62° S in the Pacific and Indian Oceans but only to 54° S in the Atlantic. The range is farther north in June to October, to about 33° S, but even farther to 6°–15° S off the west and east coasts of South America, respectively. Its populations have suffered from introduced cats and rats on Tristan da Cunha, Marion, Crozet, Amsterdam, Macquarie, and the Campbell Islands, but large populations persist on Gough Island and on the Kerguelen and Antipodes archipelagos. Recent removal of predators from Marion, Macquarie, and the Campbell Islands will benefit those population remnants. It suffers little mortality from brown (sub-Antarctic) skuas.

This is a winter breeding species, returning to colonies from February. It is active over land day and night, returning to colonies particularly in afternoons (breeders) and probably after 0300 h local (nonbreeders). Calls, mainly a pulsating bleat, are given by nonbreeders from the ground, usually near or inside a burrow. There is calling in the first 2–3 h of darkness, then quietness till about 3 h before dawn, when the greatest volume of calling occurs till birds leave at dawn. The single white egg is laid between early March and late April in 1- to 3-m-long burrows in dry terrain, particularly slopes covered with tussock grasses. The egg hatches after about 58 days in May to June, and the fledgling, alone from 3 days of age, departs after 130–163 days, rearing in late September to early December. In the Pacific, most birds move eastwards towards South America after the breeding season. There is some competition for burrows with white-headed petrels or sooty shearwaters on certain islands.

Grey petrels mostly eat cephalopods and fish, which they catch by diving or surface-seizing, solitarily or occasionally in groups. They sometimes associate with smaller toothed whales when feeding, and may follow ships.

White-Chinned Petrel *(Procellaria aequinoctialis)*

Individuals are 55 cm long and weigh approximately 1.3 kg; this is the largest burrowing petrel. It is entirely sooty black, browning variably with wear, and has some white feathers on the chin, which are most abundant in South Atlantic and Indian Ocean populations, whereas in the Pacific they are few or absent and barely visible at sea. Feet are black and the bill mainly straw coloured, appearing whitish at sea. They fly with much gliding, interspersed with brief spells of unhurried wing-beats, and seem more at ease in higher winds.

A very abundant species (conceivably 5–10 million birds, but with poor reliability in population estimates), its distribution is circumpolar with breeding colonies in the South Atlantic (South Georgia, Falkland Islands), Indian (Prince Edward, Crozet, and Kerguelen archipelagos), and Pacific (Auckland, Campbell, and Antipodes archipelagos) oceans. Its size has given it some protection against introduced predators, but cats or rats have reduced colonies on Marion and some of the Îles Crozet, and extirpated those on Cochons, Macquarie, and Campbell Islands. Mortality through bycatch in various longline fisheries in the Southern Ocean has also been threatening some populations in the last 20 years. It reaches the edge of the Antarctic pack ice circumpolarly in summer and its range moves northwards to about 30° S in winter, farther off South America and Africa, with birds tending to concentrate over continental shelves and slopes of southern South America, Africa, and Australasia. In the Pacific, the western populations move towards South America after breeding.

The 1- to 3-m long burrows are typically dug into poorly drained habitat with the entrance tunnel for drainage and the nest elevated on a peaty pedestal in the nest chamber. The breeding season is from September to June, with breeders arriving back first to mate, laying of the single white egg during November to December, and hatching after about 59 days in January to February. The chick, alone from 8 days old or earlier, is fed about every second night, with parents absent foraging about 3.8 days at a time. Fledglings depart at about 97 days old in April to early June. Nonbreeders visit the colonies from November to March, calling from the ground or at burrow entrances, uttering their prolonged rattling call. Birds arrive at the colonies mainly late in afternoons but probably also at night, with most calling in the 3 hours after dusk and before dawn, when they leave. Brown (sub-Antarctic) skuas frequently attack and kill adults and fledglings, with a pair of skuas sometimes collaborating in this.

The diet of white-chinned petrels consists mainly of fish, among which lanternfish and nototheniids are important, and cephalopods and various crustaceans, notably euphausiids. They feed by surface-seizing or diving, and often or mainly at night. Though generally solitary, they congregate at food sources such as fishing vessels, follow ships, and are the seabirds most associated with smaller toothed whales in parts of the Southern Ocean.

Michael J. Imber

See also **Amsterdam Island (Île Amsterdam); Auckland Islands; Campbell Islands; Crozet Islands (Îles Crozet); Fish: Overview; Gough Island; Kerguelen Islands (Îles Kerguelen); Macquarie Island; Prince Edward Islands; Shearwaters, Short-Tailed and Sooty; Skuas: Overview; Squid; Sub-Antarctic Skua; Zooplankton and Krill**

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PHILATELY

Antarctic mail bearing postage stamps commenced with the earliest exploratory expeditions of the twentieth century. Before official post offices were established on board ship or at the expedition base, mail was carried by ship to the expedition port for the application of postage stamps of that country, and despatch to its destination. For example, the Swedish South Polar Expedition (1901–1904) sent mail from its base on Snow Hill Island, but posted from Port Stanley bearing Falkland Islands stamps. Some expedition mails applied an official cancellation while in the Antarctic but were not stamped until arrival at port, so the cancellation did not officially cover the stamp (e.g., Mawson's Australasian Antarctic Expedition, 1911–1913).

The first official post office established in the Antarctic was for Bruce's Scottish National Antarctic Expedition (1902–1904) on Laurie Island, South Orkney Islands. Mail, bearing either Falkland Islands or Argentine stamps, was posted from Stanley (Falkland Islands) or from Buenos Aires, respectively. In 1904, the station was handed over to the Argentine government, which has manned it ever since, although the post office closed in 1905 (reopening in 1942).

The first stamps issued specifically for use in the Antarctic were for the British National Antarctic Expedition (1907–1909). Lieutenant Shackleton was sworn in as postmaster before a New Zealand magistrate and supplied with a stock of the then-current one-penny New Zealand stamps overprinted with "King Edward VII Land." For the BNAE (1910–1913), Captain Scott was likewise sworn in as a New Zealand postmaster and provided with a stock of 1d and ½d stamps overprinted "Victoria Land." For both expeditions, mail was sent from the base post office via Lyttleton, New Zealand. Admiral Byrd's United States Antarctic Expedition of 1928–1930 had on-board post offices on both the *Eleanor Bolling* and *City of New York*. Mail used current US stamps cancelled with the name of the ship (but not the territory) and date, and was posted from New Zealand. Byrd's second expedition (1933–1935) utilised the rapidly increasing popularity of Antarctic philately to contribute towards the cost of the expedition. Almost 121,000 covers were serviced at the two post offices, Little America and on board the *Jacob Ruppert,* for later sale. A special US stamp, designed by President Roosevelt, was used, together with other US and Canal Zone stamps. Later US expeditions (1939–1941, 1946–1947) also had on-board post offices (*Bear* and *Mount Olympus,* respectively, the latter handling 150,000 philatelic covers), with the ships' cancellation on US stamps.

The first commercial use of a post office was at the Norwegian *Hektoria* whaling station at Deception Island, South Shetland Islands, between 1913 and 1931. Several types of cancellation were used (Port Foster, Deception Island, South Shetlands) on contemporary Falkland Islands stamps.

During World War II, the UK government established several bases in the Antarctic Peninsula region, under the covert "Operation Tabarin," later to become the Falkland Islands Dependencies Survey, and ultimately the British Antarctic Survey. Official post offices were established at each, partly to strengthen the UK's political claim to that region (Falkland Islands Dependencies) at a time when Argentina and Chile were also boosting their claims to the same sector. Stamps of the Falklands overprinted with "South Orkneys Dependency of [Falkland Islands]," "South Shetlands...," and "Graham Land..." were cancelled with the appropriate base postmark and sent via the Falklands. From 1946 the UK, Argentina, and Chile built numerous bases, with post offices, throughout the Antarctic Peninsula sector. Many of these were short-lived, while others were opened specifically for the International Geophysical Year (1957–1958). When the French station Dumont D'Urville, together with post office, opened in 1949, it used a single overprinted ("Terre Adélie Dumont D'Urville") stamp of Madagascar. Following the adoption of the Antarctic Treaty in 1961, many national research stations operated post offices for the scientific personnel that also serviced a much greater philatelic clientele. However, of the seven territorial claimants of sectors of Antarctica, only Australia (Australian Antarctic Territory), France (Terre Adélie, but including all of Terres Australes et Antarctiques Françaises [TAAF]), New Zealand (Ross Dependency), and the UK (British Antarctic Territory) issue specific territorial stamps, with several new issues every year. All other nations operating in Antarctica use their current national stamps, some of which depict Antarctic scenes or historical events.

Every few years Australia, New Zealand, and Britain issue new definitive issues with 10–15 stamps of various denominations. Each of these is based on a theme, such as birds, marine creatures, fossils, ships that have served their national stations, explorers, research stations, etc. These nations, and France also, issue short sets of stamps commemorating some regionally relevant historical (e.g., Scott, Shackleton, Mawson, British Graham Land Expedition) or scientific (e.g., Antarctic Treaty, Scientific Committee on Antarctic Research, International Geophysical Year) event or anniversary, or some simply featuring some aspect of scientific research (e.g., dinosaurs, minerals, lichens, seals, petrels, whales, atmospheric phenomena, clothing, modes of transport, etc.). Nonclaimant countries periodically issue stamps of their country with similar themes that are also valid both in the homeland and at their Antarctic station post offices. In the case of the British Antarctic Territory, UK royal family anniversaries are also depicted.

Most of the sub-Antarctic islands operate post offices, but only South Georgia (formerly one of the Falkland Islands Dependencies) and the French Indian Ocean islands (Îles Kerguelen, Crozet, Amsterdam, and St. Paul, which, together with Terre Adélie, constitute TAAF) issue their own stamps. Between 1910 and 1947 South Georgia used stamps of the Falkland Islands with various cancellations marked "South Georgia." From 1944, the island had its own stamps (both definitives and special issues) but, for political reasons, the island's name changed periodically on the stamps. From 1944 until 1963, the stamps bore the name "Falkland Islands Dependencies" (with South Georgia included in the cancellation). Between 1963 and 1980 they became "South Georgia," reverting to "Falkland Islands

Dependencies" from 1980 until 1985 when the island (together with the uninhabited South Sandwich Islands) achieved its own government based in the Falkland Islands. From 1986, stamps then bore the bulky name "South Georgia and the South Sandwich Islands." Of the French territories, the whaling and sheep farming settlement on Îles Kerguelen operated an unofficial post office from 1909, using French stamps. From 1924 to 1929 the islands were an administrative dependency of Madagascar, and mail used a combination of French and, for registration, South African stamps. No post office operated between 1925 and the 1950s, when scientific stations opened on all four islands and the use of TAAF stamp issues commenced. Since 1947–1948, research station post offices on Macquarie and Heard Islands have used Australian stamps, while Marion Island and Gough Island (since the 1960s) have used South African stamps. The sheep settlement on Campbell Island used New Zealand stamps. As with the Antarctic issues, sub-Antarctic territory stamps illustrate thematic and commemorative topics, but only South Georgia has produced multidenominational definitive sets.

All post offices cancel their stamps with an official station postmark, which is changed every few years. Additional official and unofficial cachets are applied for philatelic enthusiasts. The British Operation Tabarin base at Port Lockroy, Goudier Island, abandoned in 1962, was restored and designated an Antarctic Historic Site and, since 1996, when the post office reopened, has been a popular tourist attraction. The island's population of 2–3 probably makes it the smallest post office in the world, yet for 3 months each year it sends out 15–20 sacks of mail.

RONALD I. LEWIS-SMITH

See also **Australasian Antarctic Expedition (1911–1914); British Antarctic *(Nimrod)* Expedition (1907–1909); British Antarctic *(Terra Nova)* Expedition (1910–1913); Deception Island; Scottish National Antarctic Expedition (1902–1904); Swedish South Polar Expedition (1901–1904); United States (Byrd) Antarctic Expedition (1928–1930); United States (Byrd) Antarctic Expedition (1933–1935); Whaling, History of**

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Polar Post. Journal published quarterly by the Polar Postal History Society of Great Britain.

PHOTOGRAPHY, HISTORY OF IN THE ANTARCTIC

In 1839–1843, James Clark Ross, in command of HMS *Erebus,* and Francis Rawdon Crozier, commanding HMS *Terror,* brought an end to an era of early Antarctic exploration. In those same years, Louis Jacques Mandé Daguerre in France and William Henry Fox Talbot in England introduced the world to the new invention of photography. It was impossible to practise those early systems in an inhospitable climate, but by the end of the century, techniques had advanced sufficiently to make photography in Antarctica feasible even if necessitating strong muscles to carry the equipment and steadfastness and application to process the plates. The *Belgica* expedition of 1897–1899 had a surgeon who also acted as a photographer. Photographs were taken during the British National Antarctic Expedition in 1901–1904 (with engineer Reginald Skelton acting as official photographer) and during Ernest Shackleton's British Antarctic Expedition of 1907–1909 (during which Eric Marshall was officially in charge of the photography, but Sir Philip Brocklehurst and Douglas Mawson did more darkroom work than anybody else), but most of the illustrative work was still undertaken by artists. In 1908–1910, Jean Charcot, leading his second Antarctic expedition in the *Pourquoi Pas?,* organised a photographic laboratory that was described as being "huge," but it did not have a specialist photographer, the scientist responsible being in charge of magnetic studies as well as photography. Inevitably, the results of such part-time activities were indifferent in quality.

When Scott was planning his second expedition, he decided to change this unsatisfactory situation and to appoint a specialist photographer who would thus become the first professional photographer to work in the Antarctic. His choice for the role was Herbert Ponting, a fellow Englishman who had emigrated to the USA in the 1890s and who had subsequently travelled the world with his cameras for the fast-developing photo agencies. Just a few years prior to accepting the invitation to join the Antarctic expedition, he had been covering the Russo-Japanese War.

Ponting could have no complaints about the resources that were put at his disposal. Scott's second-in-command, Teddy Evans, called it "a colossal photographic outfit," and Ponting used it with a single-mindedness that took no account of personal dangers or sometimes the feelings of other expedition members. Thus he braved an attack from killer whales and came close to losing equipment and his own life when leaving until the last moment a leap for safety from ice that was fast breaking up. On arriving in Antarctica, Scott told him to concentrate on his photography during the hours of daylight that were available and to leave unloading *Terra Nova* to the others. Ponting took him at his word despite the evident, if muted, grumbles of his colleagues. It is possible that Ponting extended this concentration to the exclusion of all else somewhat further than Scott originally intended, but whether that was so or not, the others exacted a revenge when, on his various expeditions, Ponting had to haul his sledge heavily laden with photographic equipment by himself without any of the assistance that could have made the task much easier.

But that would not have overly concerned him. He was dedicated to the work at hand and to obtaining the finest record possible of the expedition's work—and of the surrounding landscape complete with its fauna. He was primarily a supreme pictorialist. He typically looked into a scene and calculated the best camera viewpoint, using the most suitable lens with a particular filter if one was required. Since elements within a composition could change with conditions, he was prepared to return time and time again until all of the elements were perfect. Only then would he take a series of photographs, which he would later process with consummate care back in his darkroom at the hut, where his dedication to the task was underlined by the presence of his bed. Although relatively inexperienced in movie photography, he had practised hard before leaving England, and the footage that can still be seen to this day shows his skill at recording *Terra Nova* smashing through the ice (from a temporary and flimsy-looking platform slung out over the ship's side), and his patience later in recording the behaviour of birds, seals, and penguins at Cape Evans. The latter in particular was to point the way for the movie and TV cameramen who were to follow him south decades later. While Ponting's pictorial images are superlative, this should not be interpreted to mean he was not talented in other photographic genres. His relatively limited number of portraits of expedition members are of high quality and his searching treatment when, for example, Oates, Cherry-Garrard, and Meares sat for him makes one wish that he had taken more portraits, especially of expedition members newly returned from exhausting and dangerous sledging trips.

Ponting was undoubtedly a loner and was not an expedition member in the fullest sense of the term. But if his colleagues thought him a little odd—and blanched at the thought of posing for him since this always seemed to result in a mishap of some kind if not injury—they respected his dedication to his task and his hard work. Thus a new verb was introduced: "to pont," which meant to pose until nearly frozen in all sorts of uncomfortable positions. In addition, since the arrangement was that Ponting would spend only one year in Antarctica, he was concerned to pass on as much of his photographic knowledge as possible to other members of expedition—the young geologist Frank Debenham being the main beneficiary. All withstood the first long Antarctic winter reasonably well (catching up with developing and printing provided a valuable outlet for Ponting) and the regard and affection that Ponting came to have for Scott and for his colleagues was shown by the single-minded determination with which, subsequently, he used the still and movie record in an endeavour to safeguard their memory until his death in 1935. Ponting expressed some disappointment with what he achieved in Antarctica, particularly stressing how the rapidly changing weather affected a programme of work even if the outcome could be mitigated by "persistent effort." Despite these misgivings, Antarctica was undoubtedly the acme of Ponting's photographic achievement. Thereafter, he achieved very little professionally that was of merit, and it was almost as though he knew he could never better his performance in the far south and had determined not to try.

Frank Hurley was also a professional photographer; although younger than Ponting, he was a contemporary who went to Antarctica first with Douglas Mawson as a member of the Australasian Antarctic Expedition (1911–1914) and then with Shackleton on his Imperial Trans-Antarctic Expedition (1914–1917). An Australian, Hurley, in many ways, both as a person and as a photographer, could not have been more different from Ponting. He was lively, gregarious, and highly resourceful such that far from concentrating exclusively on his photography he became a fully fledged member of the expeditions in which he participated. This limited the time available for his photography, but this was scarcely a disadvantage because, whereas Ponting was a pictorialist who would wait endlessly for a supreme moment, Hurley was more of an opportunist who photographed events and scenes as they occurred, with less preparation. His ability to do this—and to do it well—made his coverage more complete than Ponting's, particularly as he was more fully involved with the activities of the expeditions that he accompanied, whereas Ponting, for example, never went on any of the sledging journeys from Cape Evans. Faced first with the need to rescue photographic plates and film from the stricken *Endurance* and then to destroy many of those plates as the dangerous events of Shackleton's expedition unfolded, it was typical of Hurley's resourcefulness that, in 1917, within a short time of his return to civilisation and upon being told that additional material was needed to give the record the maximum possible impact, he should agree to return to South Georgia to shoot new material. As a result, the film *In the Grip of the Polar Pack-Ice* was a success and helped to clear all of the expedition's financial liabilities.

Hurley and Ponting met in London in 1916 and obviously had high regard for each other's photography, Hurley talking about Ponting's "beautiful work" and Ponting later describing Hurley as a "crackerjack" with the camera. Significantly, Hurley, unlike Ponting, went on to lead a full photographic life that embraced six trips to Antarctica, military service in two world wars, and various commercial activities before he died in 1962.

The work of Ponting and Hurley may be interpreted to be the "heroic" period of Antarctic photography. For some decades thereafter there were few significant developments other than the use of an aerial survey camera on Byrd's successful flight over the South Pole in November 1929. However, with the passage of some 40 years and by the beginning of the International Geophysical Year in 1957–1958, the practice of photography had changed significantly. The two pioneers had exposed colour plates—the Autochrome system developed in France and Paget plates, a British derivative—but while these constituted the first basically practical colour system, they were far from perfect. By the time of the IGY, convenient roll colour film was firmly established and 35-mm cameras had greatly reduced the weight and inconvenience of the plate cameras of earlier decades—a factor of great significance to the practice of photography in a hostile environment. One of the most significant collections of photographs of this period was produced by the Swiss professional Emil Schulthess, who was accredited to the US Deep Freeze IV operation. His pictorial photographs as a body of work may be regarded as coming the closest to those of Ponting in terms of quality, and it is intriguing that, despite the appeal of colour, which is almost a universal medium in the eyes of today's amateurs and professionals alike, the most compelling images are those shot by Schulthess on black-and-white film. Perhaps this is because, save for the marvellous atmospheric effects seen in Antarctica in the early morning and late evening, it is essentially a monochromatic world that can be rendered in black and white, with its full range of tones and textures, as well as or better than it can in colour.

Expeditions are still organised to go to Antarctica, but the main emphasis is on the work of the scientific stations. Broadcast and other media organisations have brought the continent onto the world's television screens, and tourist trips are now an accepted fact. Professional photographers visit with a view to adding an Antarctic portfolio to their stock libraries. For those working professionally in Antarctica, photography is a medium for technical recording, a means of promoting the interests of their host organisations, or a matter of personal interest. For the tourist, it is the system by which the trip can be recorded and revisited in the years that follow.

Cameras, whether still or movie, film or digital, and video are compact and of high quality. Modern equipment makes photography as reliable and convenient as possible, but Antarctica is still unforgiving. Cameras need to be handled almost all of the time with gloved hands. The batteries powering cameras have traditionally been susceptible to cold temperatures, but lithium batteries are less vulnerable to draining than earlier types—and digital cameras are typically powered by batteries that can be recharged. Most cameras have auto-exposure systems incorporated, and these have to be interpreted skillfully since a typical Antarctic landscape leads to underexposure; there is thus a need to "open up" the aperture and to bracket exposures to be sure of a satisfactory result. Here again the growing popularity of professional-quality digital cameras is an advantage since they tend to display good exposure latitude, whereas the transparency film normally used by professionals—because of its inherent quality—has very limited latitude.

More than a century has elapsed since the first cameras were taken to the continent, and, perhaps because quality is sometimes directly related to the difficulty with which something is obtained, it can be argued that the work of the early pioneers such as Ponting and Hurley has never been surpassed. Quite apart from considerations of inherent quality, perhaps that evaluation stems to a degree from awareness of the difficulties and dangers that were overcome by the pioneers to secure their images and of the heroic and sometimes tragic events that were portrayed.

H. J. P. Arnold

See also **Australasian Antarctic Expedition (1911–1914); Belgian Antarctic *(Belgica)* expedition (1897–1899); British Antarctic *(Nimrod)* Expedition (1907–1909); British Antarctic *(Terra Nova)* Expedition (1910–1913); British National Antarctic (Discovery) Expedition (1901–1904); French Antarctic *(Pourquoi Pas?)* Expedition (1908–1910); Imperial Trans-Antarctic Expedition (1914–1917); International Geophysical Year; United States (Byrd) Antarctic Expedition (1928–1930)**

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PHYTOPLANKTON

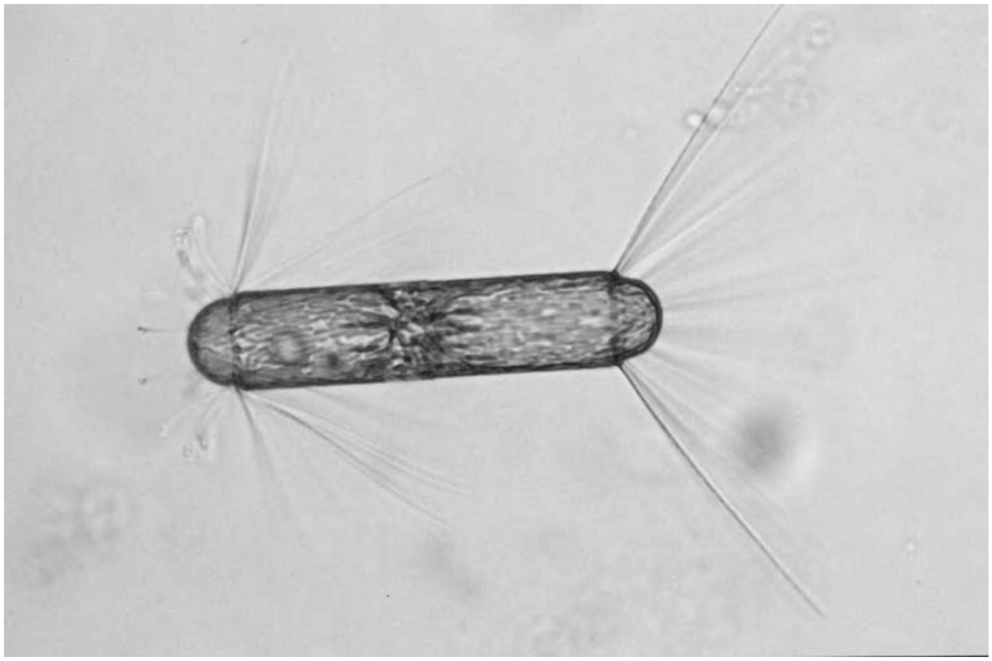
The phytoplankton are the community of free-floating single-celled plants, or algae, that live in illuminated, surface waters of Antarctic marine and freshwater habitats. The name is derived from the Greek "phyton" (plant) and "planktos" (wanderer). The cells are in most cases microscopic and, like larger multicellular plants, derive their energy from sunlight; they are therefore the main primary producers in the Southern Ocean providing the energy and nutrients that support the Antarctic marine food web. Marine phytoplankton communities are composed of a diverse range of algae but are often dominated by a small number of species that, if present in large numbers, form phytoplankton "blooms." These blooms may discolour the water and can be visible to the naked eye. Phytoplankton cells were first recorded in the Southern Ocean by J. D. Hooker, botanist on the *Erebus* and *Terror* Expedition of 1839–1843, with pioneering studies undertaken on subsequent expeditions in the late nineteenth and early twentieth centuries. They remain an important subject of Antarctic scientific research.

There are approximately 400 species of phytoplankton in the Southern Ocean belonging to several taxonomic groups of algae including the cyanobacteria, diatoms (Bacillariophyceae), dinoflagellates (Dinophyceae), silicoflagellates (Dictyochophyceae), coccolithophores (Prymnesiophyceae), cryptomonads (Cryptophyceae), and green algae (Chlorophyceae). Phytoplankton cells are usually distinguished by their size, shape, or plant pigments; however, some species can only be identified using genetic information. Many species are endemic to the Antarctic and relatively uniform in their geographic distribution due to the circumpolar circulation of the Southern Ocean.

Phytoplankton cells usually exhibit vegetative (asexual) growth but also have a sexual reproductive stage. Some cells remain attached to each other after cell division by forming chains or gelatinous colonies of up to several hundred cells. The cell walls of some phytoplankton have specialised outer layers, particularly the diatoms, which are enclosed within a siliceous frustule. As do plants, phytoplankton require light for growth but are capable of surviving the long, dark austral winter by forming resting spores or by deriving energy from extracellular organic compounds. During sea-ice formation, phytoplankton cells can become enclosed within brine channels in the ice lattice and exposed to low temperatures and high salinities. Some cells can survive and grow in such extreme conditions, and those that do may be released back into the water column when the ice melts and may "seed" a new phytoplankton population.

Phytoplankton cells are often classified into three size categories based on the linear dimensions: the picophytoplankton (0.2–2 μm); the nanophytoplankton (2–20 μm); and the microphytoplankton (20–200 μm). These size categories in part reflect the traditional method used by scientists to collect phytoplankton: the larger microphytoplankton (also known as "net" phytoplankton) are retained on plankton nets that are not able to collect the smaller phytoplankton. They also reflect differences in physiology and ecological role.

The picophytoplankton include prokaryotic cyanobacteria and tiny eukaryotic flagellates, whereas the nanophytoplankton are composed of only eukaryotic cells including small diatoms (e.g., *Chaetoceros neglectus*), coccolithophores (e.g., *Emiliania huxleyi*), crytomonads, and other green flagellates. These small cells are well adapted to grow in nutrient-poor waters due to their large surface-area-to-volume ratios; however, they are vulnerable to grazing by fast-growing single-celled zooplankton, which can exert tight control over their numbers. They therefore tend to



The diatom *Corethron criophilum,* a common species of Antarctic phytoplankton. (Photo c/o Christine Campbell, Culture Collection of Algae and Protozoa, Dunstaffnage Marine Laboratory, Oban, UK.)

exhibit small temporal and spatial variations in abundance compared to the larger phytoplankton. Picophytoplankton abundance is relatively low in the Southern Ocean in comparison with warmer tropical and subtropical seas, where they dominate the phytoplankton. By contrast, the nanophytoplankton can often dominate phytoplankton abundance, biomass, and production in the Southern Ocean, especially in offshore waters.

The microphytoplankton include large diatoms (e.g., *Corethron criophilum* and *Eucampia antarctica*), dinoflagellates (e.g., *Protoperidinium antarcticum*), silicoflagellates (e.g., *Dictyocha speculum*) and, on occasions, gelatinous colonies of smaller flagellates and diatoms (e.g., *Phaeocystis antarctica* and *Thalassiosira* spp.). These larger algae tend to dominate the phytoplankton of nutrient-rich inshore waters where they form the main food of multicellular zooplankton, including krill *(Euphausia superba)*. Microphytoplankton characteristically exhibit large temporal and spatial variations in abundance because these slow-growing zooplankton cannot respond quickly to rapid increases in phytoplankton cell numbers.

Phytoplankton production in the Southern Ocean is generally lower than in lower-latitude oceans; however, the abundance and biomass of phytoplankton are patchy, and production, which is a function of biomass and growth rate, can be locally very high. The highest production tends to be associated with coastal waters or hydrographic features, such as oceanographic fronts and eddies. This reflects the higher concentration of nutrients encountered in such areas. High phytoplankton production is also associated with the receding edge of the sea ice, where lower-salinity surface water promotes water-column stability, leading to favourable light conditions for plant growth. Light conditions in the Antarctic, and thus phytoplankton growth, exhibit strong seasonal variation, and the period of maximum phytoplankton production changes from early spring to late summer or early autumn with increasing latitude. Many animals within the Antarctic have adapted their life cycles to exploit these predictable, highly seasonal periods of marine primary production.

Antarctic marine phytoplankton communities have received considerable attention from the scientific community due to their role as primary producers and their influence on the oceanic carbon cycle. Much of this research has focused on the environmental and biological factors controlling their growth rates and biomass. Phytoplankton cells, like larger multicellular plants, require water, light, carbon dioxide, and nutrients in order to grow. The latter include nitrogen, phosphorus, silicon (required by diatoms), and trace metals such as iron. In addition, phytoplankton cells need to avoid being grazed by zooplankton or infected by viruses. In most marine environments the supply of nitrogen limits phytoplankton growth in summer months, but in the Southern Ocean the nitrogen supply is usually sufficient to meet the needs of phytoplankton. Instead, recent studies have shown that phytoplankton growth can be limited by the availability of iron, which is in short supply in offshore regions. This discovery has led to speculation that the Southern Ocean could be fertilized with iron in order to promote phytoplankton growth, thereby removing more carbon dioxide from the atmosphere and helping to slow climate change. Other factors, such as light availability, temperature, and grazing pressure, are also known to affect phytoplankton production, so the situation is complex. This therefore remains a subject of current debate.

RAYMOND LEAKEY

See also **Algae; Carbon Cycle; Climate Change; Ecosystem Functioning; Food Web, Freshwater; Food Web, Marine; Marginal Ice Zone; Marine Biology: History and Evolution; Marine Trophic Level Interactions; Pack Ice and Fast Ice; Polar Front; Productivity and Biomass; Protozoa; Sea Ice: Microbial Communities and Primary Production; Seasonality; Zooplankton and Krill**

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PLACE NAMES

Place names form an essential part of cartography. Those used on early Antarctic maps and charts reveal the history of exploration by the different exploring and scientific expeditions, in that features seen by them for the first time were named in each one's native language. The eighteenth-, nineteenth-, and early twentieth-century expeditions originated from Australasia, Belgium, France, Germany, Japan, Norway, Sweden, Russia, the United Kingdom, and the United States. By the 1940s, other nations, such as Argentina and Chile, had undertaken exploratory surveys in the Antarctic, and Spanish was added to the mix of languages used for place names. After the International Geophysical Year (1957–1958), many more countries participated in Antarctic research, and place names have been approved now by Bulgaria, Canada, China, India, Italy, Poland, and Spain.

Because early visits to Antarctica were by sea, prominent land features of value to mariners for navigation purposes, such as islands, headlands, and significant peaks, were amongst the first to be named. Many place names commemorated heads of state or members of royal families, a benefactor of the relevant expedition, or a member of the ship's company; some were descriptive of the feature being named.

A place name usually consists of two parts (generic and specific) and, with its geographic coordinates and official description, should be unambiguously identifiable. The generic part of the name indicates the type of feature, such as island, peninsula, mountain, etc., and the specific part provides a unique identifier for that feature, such as a descriptive or personal name. For example, there are hundreds of islands in the Antarctic but only one Dundee Island, named after Dundee, Scotland, the home port of the Dundee Whaling Expedition, 1892–1893. The range of specific names applied to Antarctic features is summarized in the following table.

The term "Antarctic Continent" was first used on charts published by the United States Exploring Expedition (1838–1842) under Charles Wilkes, and the name Antarctica, proposed in 1886, has been in common usage since the early twentieth century. Antarctica is now defined as the landmass lying almost entirely south of the Antarctic Circle and the offshore islands on its continental shelf. The Antarctic, however, is widely defined as the region lying south of the Antarctic Convergence, including Antarctica and the off-lying and oceanic islands, ice shelves, sea ice, and ocean.

During the early exploration period, some named features were located imprecisely on the rough maps and charts available at the time, and several were misspelled when being transcribed from one chart to another. Furthermore, features in an accessible and oft-visited location gained different names in several languages, whilst others acquired different versions of the same name when expedition volumes in which they were mentioned were translated into another language.

The duplication, translation, and misapplication of place names were already well established when increased activity on the continent in the 1920s and 1930s led to a proliferation of new place names. By then, seven nations had made territorial claims in Antarctica, and those and other nations developed

Types of Specific Names Used for Antarctic Place Names

Type of Name	Example
Descriptive name relating to size, shape, colour, number, accessibility, aspect, or similarity	Small Rock, Islotes Chatos, Blue Lake, Trio Nunataks, Inaccessible Coast, Rugged Island, Cone Nunatak, respectively
Names denoting position (relative to other features or the compass)	Mount Faraway, South Beach, West Cape
Names in association with prominent features	Lachman Crags, from nearby Cape Lachman
Names reflecting occupational use, scientific activity, or historical events	Factory Cove, Pendulum Cove, Coronation Island
Names recalling incidents during travel	Terra Firma Islands, Lost Seal Stream
Names connected with navigation	Anchorage Island, Foul Point
Mythological names and biblical names	Romulus Glacier, Mount Christi
Names of expedition leaders or ship masters	Filchnerschelfeis, Biscoe Islands
Names of royalty	Louis-Philippe Plateau, Prinsesse Astrid Kyst
Supporters of expeditions, including patrons, politicians, and donors of equipment	Beardmore Glacier, Pitt Islands, Cape Calmette, respectively
Names associated with sealers and whalers	Byers Peninsula, Foyn Coast
Names of members of expeditions	Oates Coast, Crary Ice Rise
Names of peoples and of places elsewhere	Argentine Islands, Stonington Island
Names of organizations associated with Antarctic exploration	Royal Society Range, Foundation Ice Stream
Anagrams of names already applied	Dimaryp Peak, after The Pyramid
Acronyms formed from initial letters of other words	Fidase Peak, Scar Inlet
Names founded on error	False Bay, Mistake Peak, Mount Quandary
Names derived from Greek or Latin words	Alpha Island, Mount Solus
Names emphasizing emotions	Deception Island, Cape Disappointment
Whimsical names	Phantom Point, Three Brothers Hill
Names associated with date or season	Mount Christmas, Port Circumcision, Winter Island
Names of ships that have worked in the region	Hero Bay, Jason Peninsula, Mirnyy Peak
Names derived from local geology	Coalseam Cliffs, Mount Glossopteris
Names of plants, mammals, birds, fish, and invertebrates	Cryptogam Ridge, Seal Bay, Albatross Island, Salmon Island, and Midge Lake, respectively
Groups of associated names (e.g., pioneers of medicine and aviation, composers, constellations)	Pasteur Peninsula, Wright Ice Piedmont, Beethoven Peninsula, Pegasus Mountains, respectively

Table after Hattersley-Smith (1991), with additional examples selected from Alberts (1995) and the Composite Gazetteer of Antarctica.

independent policies and procedures for naming new features. Britain established a subcommittee on Antarctic names in 1932, followed by an Antarctic Place Names Committee in 1945; it published its first list of names and their geographic coordinates as an official gazetteer in 1955. The US Special Committee on Antarctic Names was created in 1943, became the Advisory Committee on Antarctic Names in 1947, and published its first list the same year. Australia, Belgium, France, New Zealand, and Russia published lists of names or gazetteers in the late 1950s and 1960s, followed by Argentina, Chile, and Japan in the 1970s, Germany and Poland in the 1980s, and China, India, Norway, and Spain in the 1990s.

In general, Antarctic features are only named if reference to them is needed, so many Antarctic geographic features remain unnamed. Scientific stations, although man-made, have a geographic significance through their location. Whereas some national gazetteers name the stations, others do not. National gazetteers include in-shore submarine features such as bays, inlets, and straits, but names for oceanic features (e.g., seas, seamounts, abyssal plains) are the responsibility of a General Bathymetric Chart of the Oceans (GEBCO) subcommittee.

By the early 1990s, some gazetteers were available digitally and, in 1992, the Scientific Committee on Antarctic Research (SCAR), through its Working Group on Geodesy and Geographic Information, undertook to prepare both a composite gazetteer of Antarctic place names and an internationally agreed-upon set of guidelines for naming new features in Antarctica. The Composite Gazetteer of Antarctica (CGA), coordinated by Italy, was to include all named features on land and under the sea in the region south of 60° S, in the original language of the source gazetteer. The objective of the guidelines, prepared by Germany, was to avoid future translation of all or part of the name and name duplication, thus achieving one name, in its original language, per feature.

After 6 years of data collection, the CGA database held 32,955 names, representing 16,563 geographic features, contributed by 20 countries and 1 international organization (GEBCO). The CGA was published as hard copy in 1998 and released on the internet the same year; its website has been updated by Italy on a quarterly basis ever since, providing countries with the opportunity to have new Antarctic names incorporated in the CGA soon after approval by their national naming authorities. Supplements to the hard copy were published in 2000 and 2004.

Analysis of the CGA carried out by Italy in 2000 showed that there is still potential for confusion in identifying Antarctic features: more than 470 features had 2 or more completely different names, and 3377 names differed due to translation (e.g., Coronation Island and Isla Coronación) or transliteration and translation (e.g., Tizire Hyôga [Japan] and Chijire Glacier [US]). The CGA uses the Roman alphabet, and the transliteration of entries from non-Roman alphabets is as provided by the naming authority; diacritical marks (accents) are identical to those in the source gazetteers.

Responsibility for approving Antarctic names remains with the national naming authorities. Although no single legal authority coordinates the naming of features, the CGA website provides access to a truly international and up-to-date gazetteer of Antarctica.

JANET W. THOMSON

See also **Antarctic: Definitions and Boundaries; Cartography and Charting; Dundee Whaling Expedition (1892–1893); International Geophysical Year; Scientific Committee on Antarctic Research (SCAR); United States Exploring Expedition (1838–1842); Wilkes, Charles**

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PLASMASPHERE

The plasmasphere is the relatively dense doughnut-shaped region of plasma (fully ionised gas consisting of ions and electrons) that surrounds the Earth and forms the innermost region of the magnetosphere—the space around the Earth where physical processes are controlled by the extension of the geomagnetic field into space. The plasmasphere floats on top of the partially ionised ionosphere, its lower boundary usually being considered as 1000 km altitude. Above this the dominant ion is hydrogen rather than oxygen, though varying proportions of oxygen and helium ions are also present, with the total number of positively charged ions equal to the number of negatively charged electrons, thus constituting an electrically neutral gas. At night, plasma descending into the ionosphere maintains it in the absence of solar ionisation. The upper boundary of the plasmasphere is the plasmapause, which lies parallel to geomagnetic field lines; as if produced by a bar magnet at the Earth's centre, these lines link the Arctic and Antarctic polar regions and extend tens of thousands of kilometres into space. The existence of the plasmasphere was first inferred by Owen Storey in 1953 from observations of whistlers at Cambridge. Whistlers are natural radio waves with frequencies in the ELF and VLF ranges (typically a few kHz) that are generated in lightning discharges in thunderstorms and travel through the magnetosphere to the opposite hemisphere. Analysis of the whistling sound produced when a whistler is converted from radio to sound waves enables the density of electrons along its path to be determined.

Much of the early exploration of the plasmasphere was done using whistler observations from Antarctica during and immediately following the International Geophysical Year, 1957–1958. Several factors, including low levels of local interference and high thunderstorm activity in the Northern Hemisphere, make the Weddell Sea sector of Antarctica arguably the best region in the world for whistler research. The plasmapause was discovered by Don Carpenter during the early 1960s from whistlers recorded at Eights station, and independently by Konstantin Gringauz from *in situ* measurements on board early Soviet satellites.

Just inside the plasmapause the electron densities are typically 400 million per cubic meter, and energies are about 1 electron-volt, corresponding to a temperature of around 10,000°C. The plasmasphere approximately corotates with Earth. This is in contrast with the plasma outside the plasmasphere, which is an order of magnitude hotter and less dense, and does not corotate. The plasmapause is a relatively thin (about 500 km) boundary layer, typically 20,000 km from Earth, though there is a "bulge" on the dusk side. It is a highly dynamic boundary, particularly near the bulge, exhibiting plasma plumes, "bite-outs," and detached plasma regions in response to changes in the solar wind impinging on the magnetosphere. Because the plasmapause has a "footprint" in the polar regions, Antarctica remains an excellent location for studying it.

In more recent times, Antarctic measurements using fixed-frequency VLF transmissions and ULF magnetic pulsations have been used to study the plasmasphere. Now two new remote-sensing techniques—imaging of EUV radiation from plasmaspheric helium ions, and high-altitude radio echo sounding made by instruments on the IMAGE satellite situated outside the plasmasphere—are enhancing the knowledge and understanding of this key region of Earth's space environment.

Andy J. Smith

See also **Auroral Substorm; Geomagnetic Field; International Geophysical Year; Ionosphere; Magnetic Storm; Magnetosphere of Earth; ULF Pulsations**

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PLATE TECTONICS

Principles of Plate Tectonics

The concept of plate tectonics was proposed almost simultaneously in 1968 by Dan McKenzie at the University of Cambridge and Jason Morgan at Princeton University. They recognized that the Earth's solid outer zone, the lithosphere, consisted of a relatively small number of segments or plates, along whose borders most of the Earth's volcanic and seismic (tectonic) activity took place. It was originally thought that there were about ten plates in number, but they are now known to be more numerous. These plates include the continents and the lithosphere beneath the oceans. The plates move across the Earth driven by forces that are still unresolved. Because the carapace of plates is complete, the movement of each plate is constrained by the movements of all the others, and a major change in the direction or rate of motion usually causes the pattern of motion to be globally rearranged. The plates themselves were originally regarded as rigid, with all major deformation taking place at plate boundaries. Although this is mainly the case, it is now known that internal deformation can also occur.

There are three fundamental ways in which a plate may move relative to another, forming three types of plate boundaries.

1. Divergent or constructive plate boundary. Two plates may separate across a divergent or spreading boundary almost always represented by a midocean ridge such as the Mid-Atlantic Ridge. The gap is continuously filled by newly created basaltic crust, which forms the floor of our oceans by a process known as sea-floor spreading. As a result of this process, the age of oceanic crust increases away from the mid-ocean ridge. Furthermore, as new ocean floor forms, it inherits the polarity of the earth's magnetic field, forming a zebra pattern of positive and negative magnetic anomalies on the ocean floor.
2. Convergent or destructive plate boundary. Two plates may converge instead of diverge. In this case, one of the plates, usually that containing the oldest lithosphere, returns to the mantle in a zone known as a subduction zone. Subduction zones are characterized by deep trenches with an abundance of compressive earthquakes aligned along an inclined plane, the Benioff zone, which descends away from the trench at an angle of up to 60 degrees. This may occur between two oceanic plates forming a volcanic arc-trench system common in the western Pacific, or between a continental and an oceanic plate, with the volcanically active South American Andes as an example. Convergence between two plates with continental crust takes quite a different form. Subduction does not occur; instead the boundary is marked by major compressional mountain building, such as is seen in the Himalayan Mountain chain as a consequence of continent–continent collision. Compared to other convergent plate boundaries there is a marked lack of volcanic activity.
3. Transform plate boundaries. The movement of two plates need not be perpendicular; they may converge or diverge at angles of less than 90 degrees. In an extreme case, the plates may move past each other without any convergence or divergence, forming what is known as a transform plate boundary. Midocean ridges are cut by numerous transform faults ranging in size from small offsets of a few tens of metres to large offsets of a few hundred kilometers and fracture scarp lengths of several hundred kilometers.

The major tectonic events of the earth take place at the boundaries between plates: new crust is generated at divergent boundaries, and it is there also that continents break apart and new ocean basins are created. In subduction zones, old crust is recycled into the mantle beneath the lithosphere or accreted against continental margins, thereby increasing the size of the continent. The process is accompanied by mountain-building (orogeny), often involving volcanic activity. Major orogeny also occurs when two continental plates collide. Old zones of convergence and collision, called sutures, contain key records of Earth's history.

Antarctic Plate

The Antarctic plate is situated centrally about the South Pole and is one of the seven major plates present on the earth's surface. It contains the Antarctic continent and a surrounding segment of oceanic crust. The plate is separated from the neighbouring Pacific, Indian, and African plates by constructive plate boundaries that are actively spreading. On this basis, the Antarctic Plate is continuously growing, albeit at a very low rate. The boundary between the Antarctic Plate and the South American plate is complicated, as the South American plate is moving slowly to the left relative to the Antarctic Plate in an east–west direction at about 20 to 24 millimetres per year. Complications along this boundary over the past 40 million years have resulted in formation of a number of smaller plates, the Drake, Scotia, Shetland, and Sandwich plates, along the boundary zone. Starting from the triple junction between the African, South American, and Antarctic plates, the boundary between the South American and Antarctic plates is a divergent spreading ridge with long transform offsets. The boundary between the Scotia and Antarctic plates is for the most part a sinistral transform boundary, which means that the Scotia plate is moving to the left relative to the Antarctic plate across a transform fault. On the western side of southern South America, the Antarctic plate and South American plate are converging, with the Antarctic plate sinking beneath the South American plate forming a subduction zone.

As the Antarctic continent is sitting within the Antarctic plate and away from plate boundaries, the continent is noted for its low levels of volcanic and seismic activity. There are currently only two active volcanoes—Deception Island in the Bransfield Strait off the northern tip of the Antarctic Peninsula, which is related to active sea-floor spreading in a marginal (back-arc) basin due to the subduction of the Drake Plate beneath the Antarctic Plate, and Mount Erebus in the Ross Sea region, which is active and was part of a larger now mostly extinct volcanic province related to the development of an extensional rift system that formed 30–40 Ma. Seismic activity within the continent is related mainly to ice movements.

The ocean floor surrounding the Antarctic continent formed by sea-floor spreading due to the separation of the southern continents and India from Antarctica following the breakup of Gondwana 180 Ma. This has resulted in a number of large fracture zones formed as transform faults to accommodate movement between different landmasses. These include the Tasman and Balleny fracture zones, which were linked to the separation of Australia from Antarctica, which started approximately 100 Ma. In some cases, extensive volcanism related to unusually hot spots in the earth's mantle have resulted in submarine plateaus on the ocean floor. The Agulhas Plateau is an example of one of these submarine plateaus.

Scotia Plate

The Scotia Plate is a medium-sized plate located at the boundary between the South American and Antarctic plates, separating the northern tip of the Antarctic Peninsula from the southern tip of South America. The plate started to form about 30 Ma, probably due to a change in relative plate motions between the two major plates. Sea-floor spreading resulted in the opening of Drake Passage and the development of a circumpolar current, which ultimately had a profound effect on global climate systems, resulting in the cooling of Antarctica and the onset of glaciation. The plate is bounded on its northern and southern sides by the North and South Scotia Ridge, which are sinistral (left-moving) transform faults. In simple terms, the Scotia plate can be seen as an accommodation zone related to the overall westward movement of the South American plate relative to the eastward movement of the Antarctic plate. The Scotia plate has grown by a series of short-lived spreading episodes overlapping in time.

Sandwich Plate

The Sandwich plate is a small plate to the east of the Scotia plate. The plate is moving eastwards away from the Scotia plate but overriding the South American plate. Consequently it is bounded on its western side by a spreading ridge and on its eastern side by a seismically active trench, the South Sandwich Trench, where the South American plate is subducting beneath the Sandwich plate, forming the volcanically active South Sandwich Islands. The plate probably formed about 20 Ma due to a relative change of direction of the larger South American and Antarctic plates.

Drake Plate

The Drake plate is a small plate at the northwest tip of the Antarctic Peninsula off the South Shetland Islands. It is currently converging towards the peninsula margin and being subducted beneath the South Shetland Islands. This process has resulted in the development of a marginal basin, Bransfield Strait, between the South Shetland Islands and the Antarctic Peninsula. In fact, the islands moved away from the peninsula because of the formation of a new spreading system, by a process known as back arc spreading, over the past 1–2 million years. Eventually the spreading ridge between the Drake and Antarctic plates that bounds the northwest edge of the Drake Plate will collide with the trench and the Drake plate will be consumed and disappear. This is exactly what happened over the past 50 million years, as the Drake plate is the remnant of a much larger Phoenix plate, which has been consumed beneath the western margin of the Antarctic Peninsula by the subduction process. Subduction ceased over the past 50 million years due to sequential collision of transform-bounded segments of the spreading ridge with the trench.

The northeast margin of the Drake plate is bounded and separated from the Scotia plate by a fracture zone, a large transform fault called the Shackleton Fracture Zone. Movement across this boundary is sinistral, with the Scotia plate moving to the left relative to the Drake plate.

BRYAN C. STOREY

See also **Antarctic Peninsula, Geology of; Bransfield Strait and South Shetland Islands, Geology of; Drake Passage, Opening of; Geological Evolution and Structure of Antarctica; Gondwana; Islands of the Scotia Ridge, Geology of; South Pole; Volcanoes**

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POLAND: ANTARCTIC PROGRAM

In 1895, Henryk Arctowski contacted Adrien de Gerlache de Gomery, organiser of the Belgian Antarctic Expedition aboard *Belgica,* and was appointed the scientific vice leader of that expedition. Another Pole, Antoni Dobrowolski, also participated in the expedition, which lasted from 1897 to 1899 and was the first to winter in the Antarctic. That was the beginning of Poland's tradition of research in the Antarctic. In the 1960s and 1970s, several Polish scientists participated in Soviet and American Antarctic expeditions, as the country became more active in its scientific exploration.

In order to investigate living resources and fishing possibilities, Poland sent two ships to Western Antarctica in January–February 1976, as part of a research programme directed by Dr. Stan Rakusa-Suszczewski. In December 1976, two more vessels set out from Gdynia, bound for Antarctica. The plan was to establish Henryk Arctowski station. The effort was lead by Rakusa-Suszczewski, and after a short reconnaissance, Admiralty Bay on King George Island was found to be a suitable site for the base. Since its opening in 1977 the station has operated continuously. Its principal role is to serve as an ecological and earth sciences observatory. There has been continuous research in oceanography, geology, geomorphology, meteorology, seismology, magnetism, and, particularly, ecology. Furthermore, research at the Polish station is closely related to international research programmes coordinated by the Scientific Committee on Antarctic Research. Poland also organised seven Antarctic marine and oceanobiological expeditions within the Biomass programme, as well as four Antarctic geodynamic expeditions.

The present Polish national integrated programme is called "Changes and Variability of the Antarctic Coastal Ecosystems." The Department of Antarctic Biology, Polish Academy of Sciences, is responsible for the activities at Arctowski Station and for the organisation of expeditions financed by a special governmental fund (SPUB, about a million dollars yearly) of the Ministry of Scientific Research and Information Technology. The main areas within which research is conducted by the Department of Antarctic Biology are studied in cooperation with many Polish universities and institutes from which researchers join the national program as contractors. The Polish programme takes into consideration financial, logistic, and research abilities of the state. The main areas of scientific interest are as follows:

- Interaction in the near-shore zone of Admiralty Bay, King George Island.
- Monitoring of selected groups of flora and fauna and trophic relations in the near-shore ecosystems.
- Colonisation and succession in coastal and shelf ecosystems.
- Trophochemoreception in invertebrates and fish.
- Management of protected areas.

Arctowski station is visited by more than 2000 tourists every year, which is encouraged since environmental education and promotion of nature conservation have been considered among its missions from the very beginning. It is an attractive, modern, and comfortable place for scientific work, permanently hosting between ten and twenty expedition members, usually including several researchers from other countries. Poland has been undertaking initiatives relating to the protection of the natural environment in the area, facilitated by research in cooperation with Brazil, Peru, and the USA. Due to a Polish initiative, the region of Admiralty Bay has been approved by the Antarctic Treaty as an Antarctic Specially Managed Area and the west side of the Bay as Antarctic Specially Protected Area no. 128. Another ASPA (no.151) was established as a reference point in King George Bay.

STANISLAW RAKUSA-SUSZCZEWSKI

See also **Belgian Antarctic *(Belgica)* Expedition (1897–1999); Brazil: Antarctic Program; de Gerlache de Gomery, Baron Adrien; King George Island; National Antarctic Research Programs; Protected Areas Within the Antarctic Treaty Area; Russia: Antarctic Program; Scientific Committee on Antarctic Research (SCAR); Tourism; United States: Antarctic Program**

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POLAR DESERT

A widely accepted definition of a desert is a large tract of land, waterless and virtually devoid of vegetation, with negligible precipitation and usually with extremes of temperature. In this sense, almost the entire continent of Antarctica qualifies as a desert since most of its liquid water is bound in the frozen state and therefore unavailable to any form of life. Here, "polar desert" refers to those extensive ice-free areas that fit the definition above. In effect, they are the areas in which biological or ecological oases occur. Away from the immediate influence of an oasis or water source, life in polar deserts is absolutely minimal and often absent.

Antarctic deserts comprise a system of ice-free terrain ranging from valleys and mountain ranges to various smaller topographical features, and including screes or talus and boulder fields to fine mineral soils, sand, and dunes, often patterned by freeze–thaw activity within them. Melt streams are rare and temporary, while permanent lakes vary from freshwater to highly saline, often with distinctly thermal and/or salt layers. Many of these are permanently frozen, but some have a temporary moat of open water around their margins during the brief summer.

The McMurdo Dry Valleys of southern Victoria Land comprise the largest ice-free expanse (c. 4000 km^2) in Antarctica. Much smaller deserts include Bunger Hills, Vestfold Hills, and Larsemann Hills. Many smaller ice-free, almost waterless areas occur throughout the continent, especially in mountain ranges, notably the Transantarctic Mountains, Prince Charles Mountains, Sør Rondane, Pensacola Mountains, and Ellsworth Mountains.

Because of its proximity to the research stations of McMurdo (US), Scott (New Zealand), and Mario Zuchelli (Italy), the Dry Valleys have received by far the greatest scrutiny by scientists, beginning with the British expeditions of the early 1900s. This is the coldest and driest desert on the planet. Because the average annual temperature is c. –20°C, and precipitation is virtually nonexistent, liquid water is exceptionally scarce, often existing for a very short period during summer, and then often in inconspicuous places. The biota comprises a virtually invisible assemblage of phototrophic (requiring light as an energy source) and heterotrophic (obtaining nourishment from organic substances) microorganisms (notably bacteria, cyanobacteria, algae, and fungi). These, and various microinvertebrates, exist as an assemblage intimately linked with the presence of liquid water and nutrients. Mosses and lichens are absent, except occasionally in seepage areas below glaciers. In places at higher altitudes where cloud banks occasionally develop, a few lichens exist by absorbing moisture from the atmosphere and from the very rare snow that falls there. Research has revealed that this infrequent supply of water produces a closely interconnected series of events that ultimately leads to the biological production and cycling of organic carbon and related elements. Scientists are investigating the interrelationship of the biological, chemical, and physical factors to understand the biogeochemical dynamics within this cold desert ecosystem.

The microinvertebrates are essentially aquatic organisms existing in the film of water beneath stones and at the margin of temporary streams and ponds. When these habitats enter a drought phase, the organisms have remarkable survival strategies that allow them to survive for extended periods without water. Besides being exceptionally cold-hardy, at any stage of their life cycle under conditions of environmental stress, they change their morphology, lose 99% of their free water, and enter an ametabolic state known as anhydrobiosis. In this dehydrated state, the organisms are capable of being transported long distances by the wind, thus dispersing them over large distances. They resume a normal existence when liquid water becomes available again. The dominant invertebrates are nematodes, almost all microbial feeders (e.g., species of *Monhystera, Panagrolaimus, Plectus, Scottnema*), although one *(Eudorylaimus antarcticus)* is a predator. Of particular interest in these deserts, especially the Dry Valleys, is the existence of communities of bacteria, cyanobacteria, algae, fungi, and lichens within the upper 5–10 mm of coarse-grained sandstone rock. This is the most extreme terrestrial habitat on Earth, and this cryptic ecosystem is being used as an analogue in the search for former life on planet Mars.

RONALD I. LEWIS-SMITH

See also **Algae; Antarctic: Definitions and Boundaries; Cryptoendolithic Communities; Dry Valleys; Dry Valleys, Biology of; Fungi; McMurdo Station; Nematodes; Oases, Biology of; Protozoa; Ross Island; Rotifers; Soils; Streams and Lakes; Tardigrades**

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POLAR FRONT

The Polar Front is the best known of several circumpolar oceanic fronts that surround Antarctica. It separates the cold and relatively fresh Antarctic Surface Water from the warmer and saltier surface waters to the north. W. Meinardus was probably the first to report this front, based on meteorological data collected during the German South Pacific Expedition of 1901–1902. However, there is little doubt that it was known to whalers and sealers who had worked in the Southern Ocean since the early nineteenth century. The Polar Front was originally referred to as the Meinardus line, then the oceanic polar front, and then the Antarctic Convergence, the latter correctly suggesting that surface currents converge there.

The Polar Front can usually be recognized during a seaborne southward transit to Antarctica by a sharp drop in sea surface temperature and salinity, often accompanied by fog and other changes. A more reliable method of locating the front utilizes vertical meridional sections of temperature and salinity. On summer temperature sections, the front can be easily recognized as the northernmost terminus of a characteristic subsurface temperature minimum layer sandwiched between warmer layers of Antarctic and North Atlantic origin. The subsurface temperature minimum is typically defined by the 2°C isotherm at 100- to 300-m depths, but that value has to be adjusted locally from 2.5°C north of Kerguelen to 1°C in the Bellingshausen and Amundsen seas. The corresponding salinity sections usually reveal a subtle salinity minimum immediately south of the front, deepening northward. Available winter data suggest similar definitions at that time of year.

A variety of other criteria have been used to define the Polar Front position, including the salinity minimum at 200 m, the strength of thermal gradients, the position where the temperature minimum layer begins its rapid descent, and the location of sharp changes in surface silicate concentration. The 2°C isotherm limit is often preferred, in part because it also extends vertically to the sea surface in winter, and conforms with the locus of rapid temperature minimum descent. The Polar Front can range over 14° of latitude around Antarctica (48°–62° S, on average), but surface gradients of $\sim$2.7°C are almost independent of latitude, with the minimum (1.6°C–2.5°C) in September–October, and the maximum (4.8°C–5.2°C) in February. While the along-front variability of the surface temperature is small, surface signatures are shifted southward in summer.

The Polar Front is associated with a strong jet-like current that carries 1/5 to 1/3 of the 130-Sv (1 Sv = 1 million cubic meters sec^{-1}) eastward flow of the Antarctic Circumpolar Current. Transports vary with season and year; the time-averaged surface speed of the frontal jet is near 30 cm s^{-1}, but it reaches 50–70 cm s^{-1}, especially in the Drake Passage. Currents associated with this jet have been detected throughout the entire water column (i.e., down to the ocean bottom at 4- to 5-km depths). Accordingly, the front responds to bottom topography and closely follows the sea-floor relief.

The polar front separates two distinct ecosystems, with different species of phytoplankton, zooplankton, fish, seabirds, and mammals. It may also harbor species that are endemic to the frontal zone ecosystem. Satellite remote sensing ocean color data reveal a band of elevated chlorophyll concentration along the front, clear evidence of locally enhanced primary production. Penguins, fish, seabirds, and marine mammals use the front as feeding and spawning grounds. Albatrosses can complete a circumpolar journey around Antarctica in as little as 3 months along the front, thanks in part to its high productivity. Of course they also rely on the winds, which attain maximum speeds near the Polar Front.

Islands located south of the Polar Front have a typical Antarctic climate, with well-developed glaciers and snow fields. Examples are South Georgia and Bouvetøya in the Atlantic sector, Heard Island in the Indian sector, and Peter I Øy in the Pacific sector. Islands located north of the front enjoy a sub-Antarctic climate (e.g., the Falkland Islands in the Atlantic, Prince Edward Islands and Îles Crozet in the Indian sector, and the Campbell Islands in the Pacific sector). Îles Kerguelen are an exception, with a sub-Antarctic climate despite their apparent location south of the front.

At present the Antarctic sea-ice cover extends northward as the winter season progresses, but it does not reach the Polar Front. Since the frontal zone is associated with a surface convergence and enhanced biological activity, it is marked by a high sedimentation rate that has proven useful in paleoceanographic studies. This is because at times when the Antarctic Ice Sheet was larger than today, the polar front shifted north by up to 5° of latitude. The circumpolar distribution of icebergs can also be correlated with the front location, the great majority of them being observed to its south. Most icebergs disintegrate within a few days or weeks after crossing the polar front into warmer near-surface waters.

Igor Belkin

See also **Albatrosses: Overview; Antarctic Divergence; Antarctic Ice Sheet: Definitions and Description; Antarctic Intermediate Water; Antarctic Surface Water; Bouvetøya; Campbell Islands; Circumpolar Current, Antarctic; Crozet Islands (Îles Crozet); Heard Island and McDonald Islands; Icebergs; Kerguelen Islands (Îles Kerguelen); Peter I Øy; Prince Edward Islands; Sediments and Paleoceanography of the Southern Ocean; South Georgia; Southern Ocean: Biogeochemistry; Southern Ocean: Fronts and Frontal Zones**

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POLAR FRONT, MARINE BIOLOGY OF

The Polar Frontal Zone (PFZ) separates two high-speed cores of the Antarctic Circumpolar Current (ACC), namely the Sub-Antarctic Front (SAF) to the north and the Antarctic Polar Front (APF) to the south, and represents a transition zone between the less productive, warmer sub-Antarctic waters and the cooler, more productive Antarctic surface waters. The geographic boundaries of the PFZ are difficult to identify, as the positions of the SAF and APF demonstrate a high degree of variability, both spatially and temporally. The variability in the position of the fronts is the result of several factors, including the interaction of the ACC with prominent bottom topography (so-called topographic steering) and seasonal wind patterns. The position of the fronts largely determines the geographic extent of the PFZ. For example, topographic steering in the region of the Crozet and Kerguelen Plateaux and in the vicinity of the South-West Indian Ridge may result in the SAF and APF converging into a single prominent feature, which reduces the PFZ into a narrow band. Nonetheless, the PFZ can broadly be defined as the region between 48° and 50° S.

Both the SAF and the APF have been shown to represent important biogeographic barriers to the distribution of phytoplankton and zooplankton. However, mesoscale features such as the warm- and cold-core eddies generated by flow instabilities of the SAF and APF may regionally (in the Indian sector of the Southern Ocean) assist the transfer of plankton species across the fronts. The waters in the frontal regions are usually characterised by increased biological (phytoplankton and zooplankton) activity. The elevated phytoplankton biomass in the region of the fronts is thought to be associated with localised water-column stability that promotes the growth of the larger nanophytoplankton (2–20 μm) and microphytoplankton (>20 μm). Just as the elevated phytoplankton biomass in the region of the fronts is due to an increased contribution of larger phytoplankton cells to total phytoplankton abundance and biomass, the elevated zooplankton biomass in the region of the two fronts is linked to a high contribution of larger macrozooplankton (>2 cm), mainly euphausiids, chaetognaths, and tunicates, to total zooplankton biomass. The elevated zooplankton biomass in the region of the fronts is thought to be a response to the increased phytoplankton availability. Due to increased zooplankton biomass, the frontal regions represent important foraging grounds for top predators, including flying seabirds, penguins, and seals.

The phytoplankton biomass and production in the open waters of the PFZ are generally low (<1 mg chl-a m^{-3} and <250 mg C m^{-3} d^{-2}) and usually dominated by small picophytoplankton (<2 μm). The low values recorded in the open waters can be ascribed to persistent wind patterns that generate deep-water mixing, which favours the growth of the smaller phytoplankton. Exceptions are recorded in the waters surrounding the numerous oceanic islands (Prince Edward, Crozet, and Kerguelen Islands) within the PFZ, which demonstrate the so-called "island mass effect" of increased phytoplankton biomass and production. In these regions, total chl-a concentration and production may be >2 mg chl-a m^{-3} and >300 mg C m^{-3} d^{-1}, respectively. The microphytoplankton (>20 μm) comprising mainly diatoms contribute most to phytoplankton biomass and production in these regions. The elevated phytoplankton biomass and production values recorded in the waters surrounding the oceanic islands can be attributed to localised water-column stability and increased macronutrient and trace metal (Fe) concentrations generated from freshwater runoff from the islands.

A key feature of the zooplankton community within the open waters of PFZ is the extreme spatial and temporal variability in the community structure, species composition, and biomass. Because the PFZ represents a transition zone between sub-Antarctic and Antarctic surface waters, coupled with the fact that the region is characterised by the presence of both warm- and cold-core eddies, the plankton are represented by species that are Antarctic, sub-Antarctic, and sub-Tropical in origin. Although variable, total zooplankton abundance and biomass in the open waters of the PFZ is typically $<10^4$ ind m^{-2} and biomass <100 mg Dwt m^{-2} with the highest values recorded in summer. Winter values are typically 25–50% lower than the summer values.

The zooplankton species composition in the PFZ demonstrates little or no seasonality. The total zooplankton community is numerically and by biomass dominated by mesozooplankton (200–2000 μm) comprising mainly small copepods (*Oithona, Clausocalanus, Ctenocalanus* spp.), pteropods *(Limacina retroversa),* amphipods *(Themisto gaudichaudii),* and chaetognaths (*Sagitta gazellae* and *Eukrohnia hamata*). The contribution of the different groups to the total zooplankton abundance and biomass demonstrates a high degree of unevenness reflecting the complex oceanographic environment. Although the total zooplankton biomass may at times be dominated by euphausiids (*Euphausia vallentini* and *Thysanoessa vicina*) and tunicates (mainly *Salpa thompsoni*), the contribution of the larger zooplankton to total zooplankton biomass is generally <20% of the total.

A number of studies have investigated the ecological role of the zooplankton within the PFZ. While the larger macrozooplankton may locally represent important consumers of phytoplankton production, seasonal grazing studies indicate that the most important consumers of phytoplankton production in the open waters of the PFZ are small copepods and pteropods. The low grazing impact of the macrozooplankton can be attributed to their low abundances and the predominance of small picophytoplankton within the region, which are too small to be grazed efficiently by the larger zooplankton. The copepods in turn represent the dominant component in the diets of the large numbers of predators (amphipods, chaetognaths, and euphausiids) that characterise the zooplankton assemblages of the PFZ. The large numbers of predators within the area are thought to play an important role in increasing the biologically mediated carbon flux to depth through diel vertical migrations and the production of large faecal pellets with fast sinking rates. These factors combined would serve to increase the localised efficiency of the biological pump.

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See also **Circumpolar Current, Antarctic; Copepods; Pelagic Communities of the Southern Ocean; Phytoplankton; Polar Front; Productivity and Biomass; Southern Ocean: Fronts and Frontal Zones; Zooplankton and Krill**

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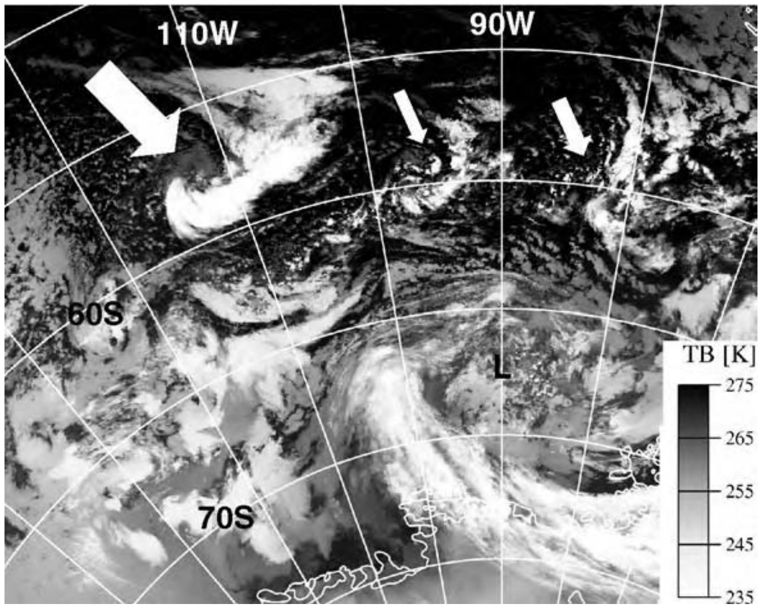
POLAR LOWS AND MESOSCALE WEATHER SYSTEMS

Types of Vortex and Formation Areas

Polar lows and mesoscale cyclones in the Antarctic were not detected until the advent of high-resolution satellite imagery from polar orbiting satellites. Unlike their counterparts in the Arctic, no historical reports about hazards associated with these systems are known, because of the fact that the Antarctic represents a huge area almost free of observational data from ships and surface stations. As a consequence, most of our knowledge about the structure of these systems relies on satellite remote sensing, but invaluable information about the governing processes has also been provided by the improvement of mesoscale numerical models during the last decade.

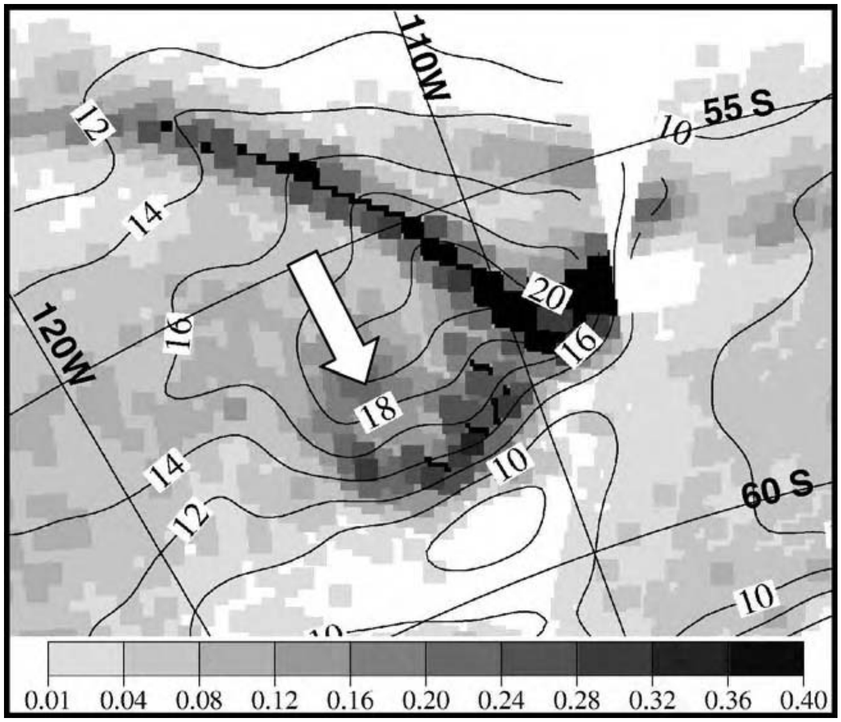
The term "mesoscale cyclone" (MC) is generally used for cyclonic vortices poleward of the Polar Front up to a horizontal scale of 2000 km. The term "polar low" represents a subgroup of intense maritime MCs with scales smaller than about 1000 km and a



AVHRR channel 4 image (mosaic) from AVHRR data (brightness temperature scale in K) for 14 UTC January 11, 1995. The main MC is marked with a large arrow; two minor MCs are marked with small arrows. The centre of the synoptic cyclone is marked "L."

near-surface wind speed exceeding 15 m s^{-1}. Antarctic MCs have been observed in different regions of the Antarctic by means of satellite imagery, geophysical parameters retrieved from satellite data, and—in the few cases where a MC was close to a research station, a ship, or automatic weather stations—by direct observational data. Climatologies of Antarctic MCs are mainly based on satellite imagery and show that MCs at the meso-α (200–2000 km) and the meso-β scale (20–200 km) occur frequently over the Southern Ocean and in the coastal regions of Antarctica. The typical diameter is less than 500 km, and they typically last less than 24 hours. Although these systems are generally not as intense as the sometimes destructive polar lows of the Northern Hemisphere, they can still complicate logistical operations (e.g., aviation) in the Antarctic and could be important in a climatological sense (e.g., by increasing the exchange of momentum and heat between polar and subpolar regions).

The detection of Antarctic MCs using satellite imagery and hence the identification of preferred formation areas depends on the spatial and temporal resolution of the satellite data. For example, most of the MC developments over the large ice shelves could be detected only by satellite imagery with high resolution, such as directly received AVHRR (Advanced Very-High-Resolution Radiometer) data. Since these data are not stored aboard the satellite, an AVHRR receiving station is needed in the area of interest in the Antarctic. Although the number of operational AVHRR stations has increased in recent years, a long-term whole-year climatology for the whole Antarctic using these data is still not available. Satellite-based MC climatologies are therefore limited to a few studies for the full hemisphere with a coarse resolution as well as a couple of regional MC climatologies using high-resolution satellite data. Because of the laborious effort associated with these studies, the maximum time period is less than 10 years. However, the results available so far indicate two different types of preferred formation areas of Antarctic MCs. The first type is represented by the transition zone of the continental ice sheet and the ocean or ice-shelf areas. Many MCs with a lifetime of often less than 12 hours develop over ice-shelf areas and close to the coast. The preferred formation areas are associated with coastal polynyas and confluence zones of the katabatic wind, in particular in the Ross Sea and Weddell Sea regions. During wintertime, the sea-ice front extending far to the north represents another preferred formation area for MCs. The interannual variability of MC frequencies is large. Since the triggering of mesocyclogenesis by large-scale cyclones is important, the general circulation patterns of the higher southern latitudes and their teleconnections to the midlatitudes and the tropics are important factors for the observed MC variability. In particular, the El Niño–Southern Oscillation (ENSO) teleconnection is considered to influence MC formation in the Antarctic.

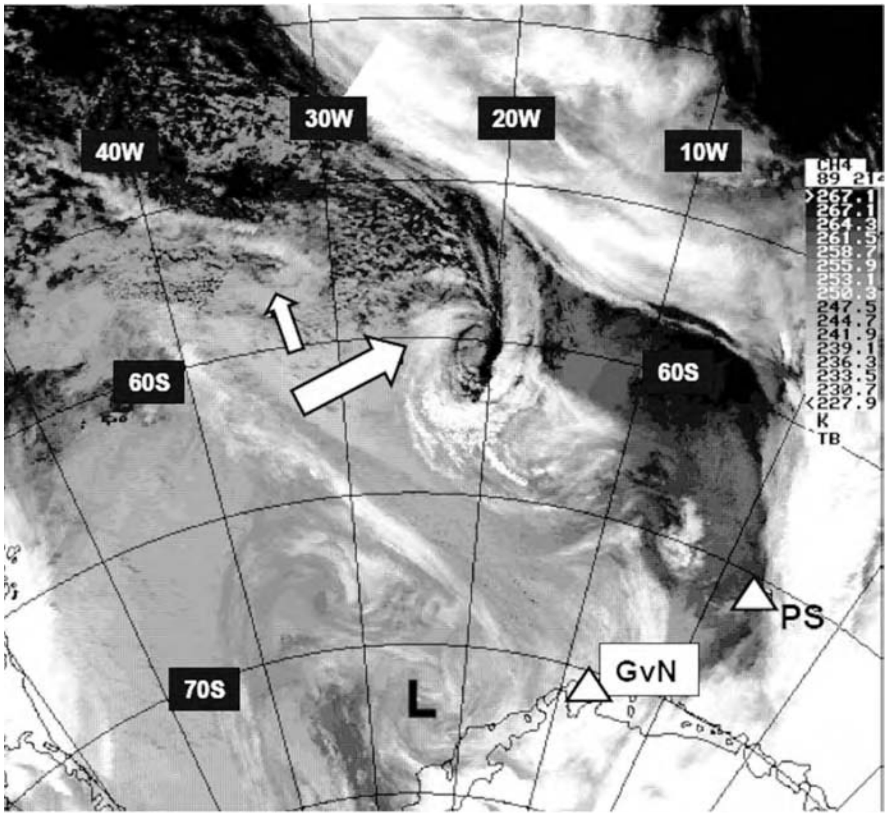


SSM/I-derived cloud liquid water (grey shaded, scale in kg m^{-2}) and near-surface wind speed (contour interval 2 m s^{-1}) for 1126 UTC January 11, 1995.

Structures of the Systems: *In Situ* and Satellite Observations

An example of a satellite-based structure analysis of a polar low developing over an Antarctic ocean is shown in the satellite image of a family of three mesocyclones developing on January 11, 1995 over the northern Bellingshausen and Amundsen Sea. This was observed by means of AVHRR, European Remote Sensing Satellite Scatterometer (ERS-SCAT), and Special Sensor Microwave/Imager (SSM/I) data. The most pronounced MC at 112° W, 58° S had a diameter of about 800 km and a lifetime of more than 24 hours, and it reached the intensity of a polar low. Low-level clouds near the centre and midlevel clouds south of the centre clearly indicated the circulation associated with the MC, and the appearance of the MC on the satellite images resembled a short baroclinic wave with shallow convection west and north of the centre. The centre of a large-scale cyclone (marked "L") remained almost stationary at 90° W, 67° S. The MC is present as a distinct mesoscale signal in SSM/I retrievals of cloud liquid water, near-surface wind speed, and integrated water vapour (not shown). In contrast to AVHRR images, where only the highest cloud layers contribute to the radiance signal, the SSM/I-derived cloud liquid water represents the whole atmospheric column. Compared to the infrared imagery, the baroclinic cloud structure of the MC is much clearer in the cloud liquid water field, because the high cirrus clouds are almost transparent at microwave frequencies. ERS-SCAT data are available for this period, but ERS-derived wind vectors give no insight into the structure of this MC, because of the narrowness of the ERS swaths. Nevertheless, these data have been used to validate numerical simulations for this case study.

The very rare case that an MC developing over the ocean passes directly over an observation station occurred for a MC event during the Winter Weddell Sea Program (WWSP) field phase 1986, when observational data were available from the German R/V *Polarstern,* situated close to a MC on July 31, 1986. The MC developed close to the sea-ice front over the northern Weddell Sea and moved over the sea ice towards the Antarctic coast during its further development. On August 1, 1986 the centre of the MC lay close to the research station Georg von Neumayer (GvN, 8.4° W, 70.6° S) at a distance of about 300 km. The satellite image on 31 July 1986 shows a synoptic-scale cyclone (L) with its main centre close to the Antarctic coast at 24° W, 71° S and the well-developed MC at 20° W, 60° S. The diameter of the MC is about 700 km, and the cloud structure reveals similarities to a short baroclinic wave, and cloud top

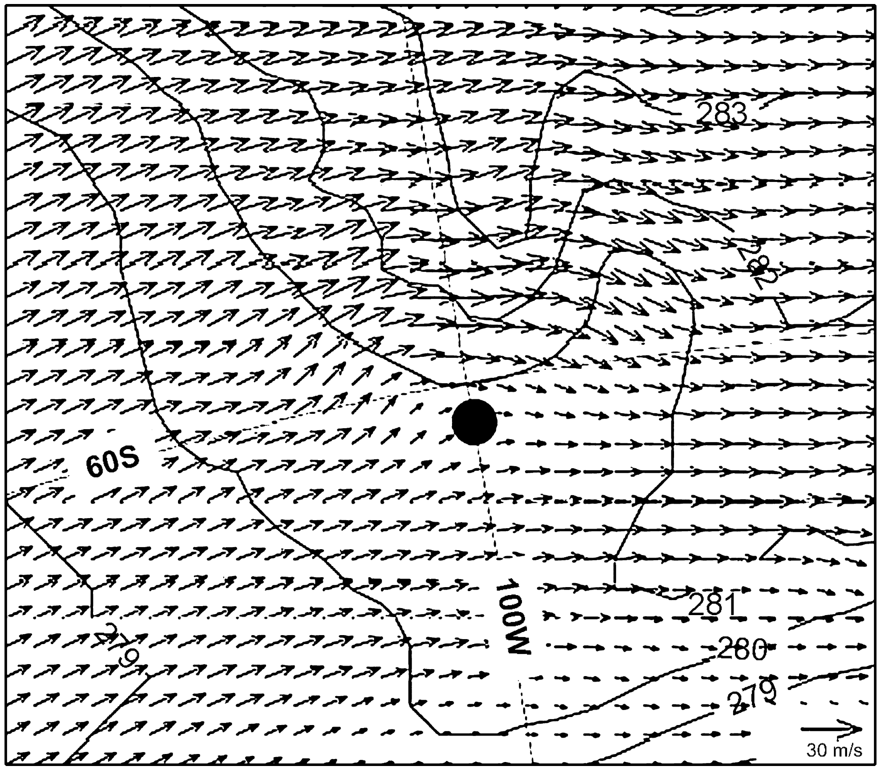


AVHRR infrared image from AVHRR data (brightness temperature scale in Kelvin) for 02-04 UTC on July 31, 1986. The main MC is marked with a large arrow; a minor MC is marked with a small arrow. L marks the centre of a synoptic-scale cyclone. Positions of the R/V Polarstern (PS) and the German research station GvN are indicated.

temperatures of the cloud band east of the centre were about –40°C. This cloud band is associated with the cold front passing over the position of the R/V *Polarstern* (PS) later on. During the approach of the MC to both stations on 31 July, the wind at GvN turned from north to east, and wind speeds increased to values of around 25 m s^{-1} for about 12 hours. The main cloud band of the MC passed over PS around 00 UTC on 1 August, which was associated with a strong temperature fall during the second half of 31 July and a wind peak of 16 m s^{-1} during the frontal passage at 1 August 00 UTC. Series radiosonde profiles obtained at GvN with a resolution of 3 hours showed the cold front as a strong inversion at 930 hPa capping a shallow layer of cold air of about 50-hPa thickness.

Structures and Dynamics: Numerical Simulations

In recent years, mesoscale numerical models have proven to be capable of successfully simulating Antarctic MCs. Simulations for realistic case studies and idealized numerical simulations using full-physics mesoscale models have contributed significantly to the current understanding of mesocyclogenesis in the Antarctic. Three mechanisms are found to be important for the formation and development of Antarctic MCs: baroclinic, barotropic, and convective dynamics. The mechanism of baroclinic instability is well known for cyclones of the midlatitudes and represents the conversion of potential energy (given by horizontal temperature gradients) to kinetic energy. In midlatitudes the preferred cyclone scale by this mechanism is several thousands of kilometers, and the cyclone extends vertically throughout the troposphere. In contrast, the vertical temperature stratification during conditions of MC formation at polar latitudes reduces the vertical scale of the baroclinic cyclones, which results also in a much smaller horizontal scale. A good framework for the understanding of classical baroclinic developments is the so-called isentropic potential vorticity (PV)-thinking, which explains the baroclinic cyclone intensification by a mutual interaction between a low-level PV anomaly and an upper-level PV anomaly upstream of the surface low. Barotropic dynamics in the form of



Mesoscale model simulation with 25 km resolution after 12 h simulation time (valid at 18 UTC January 11, 1995) for the potential temperature (full lines, isolines every 1 K) and wind vectors (every grid point) at 850 hPa. A scaling vector is shown in the lower right corner. The solid dot marks the MC centre.

orographic forcing are important for MC developments near the continental slopes. Downslope winds in and above the atmospheric boundary layer over the slopes of the Antarctic ice sheet cause a vertical stretching of the air, which leads to a barotropic vortex generation, since the conservation of PV requires the production of cyclonic relative vorticity. Among the convective dynamics theories being proposed for polar low formation, the wind-induced surface heat exchange (WISHE) mechanism seems to be present for many MC developments in the Antarctic. This mechanism represents a positive feedback between the surface heat fluxes related to the surface winds and the moist convection associated with latent heat release at upper levels. However, observational as well as modelling studies show that a combination of instability mechanisms is always present during the formation of Antarctic MCs.

For coastal mesocyclone developments the role of the katabatic wind in the formation process was investigated using high-resolution mesoscale models. A generally stable stratification in the boundary layer over the ice slopes of Antarctica leads to the development of a katabatic wind system with downslope wind speeds of 20 m/s and more. Without additional synoptic forcing, the katabatic flow is generally confined to a shallow layer over ice slopes and dissipates relatively soon after crossing the coastline or over the ice shelves. Studies of near-coast developments have revealed the interaction between the synoptic-scale environment, the katabatic wind over the ice slope, and the mesocyclogenesis. Under favourite synoptic flow, a barotropic spin-up of cyclonic vorticity corresponding to an initial mesocyclone at the coast occurs, which may be further intensified by other processes like WISHE or upper-level forcing. For MCs occurring over the Antarctic oceans or near the sea ice front, upper-level forcing was found to be present in most of the cases (i.e., these MCs can be regarded as short baroclinic waves). Convective dynamics are less important than for polar lows in the Arctic, but the intensification process of Antarctic MCs was found to depend on diabatic processes like latent heat release, particularly for wintertime cases near the sea ice front. Forcing by surface energy fluxes and intensification via the

WISHE mechanism plays an important role for the initial phase of wintertime MCs developing over open-water areas.

The simulation of observed Antarctic MCs using limited-area mesoscale numerical models is limited by the quality of the analyses (being used as initial and boundary fields), which are poor compared to the Northern Hemisphere because of the sparse observational network in the Antarctic. However, the increased amount of satellite remote-sensing data being assimilated in the operational global analyses (e.g., analyses of the European Centre for Medium-Range Weather Forecasts [ECMWF]) has led to an improvement of the initial and boundary fields for mesoscale numerical models in the Antarctic and allows more frequent successful simulations of Antarctic MCs. For example, a comparison of images from AVHRR data obtained January 11, 1995 shows both the main MC and a simulation result using a mesoscale model with 25-km resolution for that MC. The wind vector field and potential temperature at 850 hPa reflect the mesoscale circulation of the MC (superimposed on the strong zonal wind) with the circulation centre at about 100° W, 60° S. The temperature field reveals moderate baroclinicity and a wavelike structure. The result is an advection pattern resembling that of a short baroclinic wave. The intensification of the low-level circulation is triggered by a shortwave 500-hPa trough. The maximum upward vertical velocity at 700 hPa lies downstream of the 500- hPa trough axis and over the low-level circulation centre. The numerical model results show the MC as a shortwave baroclinic development triggered by an upper-level trough.

Numerical simulations of topographically forced MCs in coastal regions of the Antarctic continent show that the topography of the coastal regions plays an important role in mesocyclogenesis. One key factor is the katabatic wind system, which is able to initiate low-level MCs in areas of a suitable orography structure. In particular, the area of the southern Ross Sea exhibits a bay-like structure, where many MC developments are observed and also numerically simulated. The second key factor is the support by the synoptic environment, leading to vorticity production by vertical stretching of the synoptically supported katabatic winds. Besides this stretching mechanism, katabatic winds can have a second impact on the generation of MCs by transporting cold air into the coastal areas and thereby enhancing the low-level baroclinicity. A large fraction of short-lived coastal MCs seem to be generated by these mechanisms. For larger-scale and long-lived MCs, the amplification of a near-surface perturbation is found to occur in association with the approach of an upper-level potential vorticity anomaly. The initial low-level perturbations, however, seem to be strongly connected to specific topographical features. Since satellite-based climatologies only include MCs associated with cloud formation, a considerable fraction of topographically forced MCs will remain undetected in areas without a mesoscale observational network.

Contemporary Problems and Future Research

Compared to the Arctic, where the forecast of polar lows belongs to the routine tasks of the weather services, the number of investigated cases for the Antarctic is relatively small. In addition, the tools for validating the numerical forecasts (or even the initial analyses) are much more restricted in the Antarctic due to the sparse observational network. As a consequence, retrievals from satellites have to be used for validation purposes in most cases, which has attained increasing importance with the advent of microwave imagers and scatterometers. These sensors allow the determination of the near-surface wind and integrated water parameters for almost all weather conditions, with a resolution corresponding to that of coarse mesoscale numerical models. Future mesocyclone research in the Antarctic will increasingly use a combination of satellite data, direct observations, and numerical model data. Assimilation of satellite-retrieved geophysical parameters in a numerical model in the form of a mesoscale objective analysis is needed. A high resolution of the model is also essential. Horizontal grid resolutions on the order of 10 km (and nonhydrostatic models) are needed, but so is a high vertical resolution describing the stable boundary layer over the Antarctic ice sheet as well as low-level mesoscale fronts. Special observational programs like the First Regional Observing Study of the Troposphere (FROST) and the planned Antarctic Regional Interactions Meteorology Experiment (RIME) are the only way of getting an improved observational network as well as databases of conventional and satellite data that are easily accessible for the research community.

Günther Heinemann

See also **Atmospheric Boundary Layer; Clouds; Germany: Antarctic Program; Polar Front; Polynyas and Leads in the Southern Ocean; Remote Sensing; Ross Ice Shelf; Synoptic-Scale Weather Systems, Fronts and Jets; Surface Energy Balance; Teleconnections; Wind**

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POLAR MESOSPHERE

The mesosphere is that part of the earth's atmosphere that extends from approximately 50 to 95 km altitude. It is the coldest of the atmospheric regions and lies above the stratosphere and below the thermosphere. Its defining characteristic is that the ambient temperature drops with increasing altitude throughout. At the upper limit, the mesopause, a temperature minimum is reached. Above that, the thermosphere begins and temperatures rise sharply due to the absorption of the sun's extreme ultraviolet radiation by oxygen. Similarly, below the mesosphere, in the stratosphere, heating is primarily caused by the absorption of solar radiation at ultraviolet wavelengths by ozone. In the mesosphere itself, however, absorption of solar radiation is less dominant and other processes become equally important. Temperature changes in the mesosphere can be driven by the indirect action of atmospheric waves propagating up from the troposphere, by exothermic chemical processes, and by radiation of energy into space via carbon dioxide.

Many books and internet sites perpetuate the idea that the upper limit of the mesosphere occurs at around 80 km. However, it is now known that the height of the mesopause varies considerably with season and is always higher than 80 km. In the winter hemisphere, and extending across the equator to about 40° latitude in the summer hemisphere, the mesopause occurs at approximately 100 km altitude; in the summer hemisphere above 40° latitude it drops to around 88 km. At the equinoxes the mesopause occurs near 100 km throughout both hemispheres.

The cold air of the mesosphere overlies the warmer air of the stratosphere. This, together with its negative vertical temperature gradient (lapse rate), makes the mesosphere relatively unstable and turbulent compared to the stably stratified stratosphere. It is a dynamic region where winds regularly exceed 100 km per hour, where large atmospheric tides occur, and where a wide spectrum of atmospheric waves exists with oscillation periods from a few minutes to many days. Wave breaking and turbulence are commonplace. The air at the mesopause is some 3 million times less dense than air at the earth's surface. There is five thousand times more atmosphere (by mass) below the bottom of the mesosphere than above it. That the mesosphere contains less than one five-thousandth of the total atmosphere by mass might appear to make its presence inconsequential, but it has gained importance over recent years because it is the region where ice clouds form on the edge of space; it can be a sensitive indicator of global change; and it is a region where atmospheric waves, propagating up from the troposphere, break and drive middle atmosphere circulation on a global scale.

The polar mesosphere is of special interest because the mesopause at latitudes poleward of about 50° can have the coldest temperature anywhere in the earth's natural environment. Somewhat paradoxically, these extreme low temperatures occur during summer (i.e., November through February in the Antarctic and May through August in the Arctic). Then the temperature drops to around –140°C, several tens of degrees centigrade below the lowest-ever-recorded temperature on Antarctica's surface. This cold summer polar mesopause, some 70°C below the temperature expected under simple radiative equilibrium, is created due to the action of atmospheric waves on middle atmosphere circulation. Gravity waves, which can be generated by the impact of weather on mountains or by shear in the lower atmosphere, have to grow in size in order to conserve energy as they travel upwards into the increasingly rarefied air. When they reach the mesosphere these amplified waves can break, like waves approaching a beach, and transfer their momentum to the horizontal winds. This indirectly drives a summer-to-winter pole-to-pole circulation, which, in order to conserve mass, requires air to move upwards at the summer pole and downwards at the winter pole. When this air is driven upwards it adiabatically expands and thus cools down, markedly reducing the summer mesospheric temperature.

These cold temperatures lead to three important polar phenomena—noctilucent clouds (NLC), polar mesospheric clouds (PMC), and polar mesosphere summer echoes (PMSE). These are all closely related because each is a consequence of minute ice particles, a few tens of nanometers in size, growing near the very cold mesopause. It is these phenomena, primarily occurring in the Antarctic and Arctic, that can be sensitive indicators of global change. The mesosphere is extremely dry and so it is difficult for ice particles to form at all. There is less than 10 parts per million by volume of water at this altitude and the ice will only form when the temperatures are low enough to produce supersaturation. Thus, if the overall temperature in the mesosphere drops by only a few degrees there will be more occasions when conditions favour ice-particle formation and so the occurrence probability of NLC, PMC, and PMSE will increase markedly. Atmospheric models have shown that while an increase in the concentration of "greenhouse gases" such as carbon dioxide and methane in the atmosphere will increase temperatures near the earth's surface, it will decrease temperatures in the mesosphere and above due to increased infrared radiation out into space. Not only will the temperature decrease but the magnitude of that temperature change will be five times larger in the mesosphere than near the ground. Consequently, the mesosphere is inherently more sensitive to greenhouse gases and, advantageously, NLC, PMC, and PMSE provide us with a sensitive means of detecting that change. It is also possible that increased greenhouse gases can lead to increased occurrence of ice in the mesosphere through an increase in mesospheric water vapour content brought about through a higher methane concentration.

Noctilucent clouds (NLC) are visible to the naked eye, but only in twilight conditions. These clouds are the highest on earth and exist on the edge of space some 85 km above the ground—when you peer out of an aircraft window and look down onto weather clouds, these noctilucent clouds are still 50 miles above you. Their great altitude means that when the sun is just below the horizon, its light can still shine onto the underside of the ice particles making up the clouds and be scattered back down to the observer, who is standing in relative darkness. NLC are so optically thin that they scatter less than 1 part in 1000 of light incident upon them. This faint reflection appears brightly against the darkened sky as a silvery-blue veil that frequently exhibits fixed wave patterns as brighter streaks and bands. These patterns, reminiscent of ripple patterns on the bottom of a swimming pool, are caused by atmospheric gravity waves with wavelengths of several tens of kilometers that compress and rarefy the air containing the ice particles to create denser and thinner clouds respectively. As a consequence of the geometry between sun, cloud, and observer required to see these clouds and also the fact that they only occur in summer near the poles, they are generally only observable between latitudes of 50° and 65° near sunrise and sunset for about 3 months per year in each hemisphere. The presence of NLC was first recorded in the summer of 1884 after the eruption of Krakatoa that occurred in 1883. There have been suggestions that NLC occurrence has doubled over the past 40 years and this has been attributed to increasing anthropogenic greenhouse-gas pollution. Others now argue that this increase is only a consequence of observation statistics. While NLC are frequently seen in the Arctic, they are reported less often in the Antarctic because the distribution of land mass and the extremely low number of inhabitants makes observation far less probable.

Powerful laser beam pulses can be fired up to the mesosphere with lidars (laser radars). Below about 80 km altitude the light intensity scattered back to the ground by the molecules in the air is closely related to atmospheric density and temperature. Above 80 km the atmosphere is so tenuous that the scattered return is too weak to detect and so the laser beam frequency is carefully selected to resonate with metal atoms naturally present in the atmosphere at those heights. These are usually sodium, potassium, or iron and are a consequence of meteors burning up on entry to the earth's atmosphere. The resonating metal atoms reradiate light back to the ground and from these returns the temperature profile above 80 km can be determined. Lidars can also be used to reflect off noctilucent clouds to determine their height and denseness. Lidar measurements suggest that noctilucent clouds occur at slightly higher altitudes in Antarctica because the orbit of the earth brings it closer to the sun in January than in July and thus produces greater upwelling of the Antarctic summer atmosphere.

Polar mesospheric clouds (PMC) are essentially the same phenomenon as noctilucent clouds but are observed from above by spacecraft. One small difference lies in which particle size provides the strongest response from space compared to ground-based observations. Comparisons by polar orbiting satellites suggest that the brightness of Antarctic PMC is less than that of Arctic PMC. This lends weight to the notion that the temperature in the Antarctic summer mesosphere is a few degrees warmer than that in the Arctic. There is recent evidence that the brightness of PMC is increasing with time as a consequence of global change.

Ground-based radar, which uses the time delay of radio wave pulses to measure the distance of atmospheric targets, can observe an extra layer of echoes coming from mesospheric heights during the summer in the polar regions. These are polar mesosphere summer echoes or PMSE. These anomalously intense echoes come from a thin layer a few kilometers below the mesopause and are thought to be generated as a result of electrically charged ions accumulating on the ice particles and reducing the diffusivity of electrons so that very small-scale structure in electron concentration can exist. There has been some evidence that PMSE, like PMC, may be weaker in the Antarctic than the Arctic, but further observations are required to confirm or deny this.

Making direct measurements in the mesosphere is challenging. It lies above the altitude of the highest balloons and below the altitude of satellite orbits. *In situ* measurements can only be made using rockets and are therefore very transitory and expensive. The first *in situ* temperature profiles of the Antarctic mesosphere were not measured until 1998 using falling spheres. These 1-m-diameter inflatable mylar spheres are ejected above the mesosphere from meteorological rockets at approximately 115 km altitude. From there they initially plummet towards the ground because the air is so tenuous, but the drag of the air gradually slows them down until, at around 30 km, the atmospheric pressure destroys them. By tracking the descent of the spheres with a high-power radar and applying drag equations to the derived trajectory, it is possible to calculate the atmospheric density and temperature with 100-m-altitude resolution. These falling sphere measurements indicated that January mesopause temperatures in Antarctica (after solstice) were just as cold as those in July in the Arctic, but measurements at summer solstice itself were unable to be made because of the seasonal limitations of shipping the rockets through the Antarctic sea ice.

There is scientific debate about whether mesospheric temperatures in the Antarctic summer are warmer than those in the Arctic summer. The evidence for weaker PMC and PMSE in Antarctica has been used to support the argument that the Antarctic summer mesosphere is warmer. Conversely, however, the falling sphere measurements support the alternative argument, that Arctic and Antarctic summer mesopause temperatures are equal.

Why do contrasts between the Antarctic and Arctic mesosphere matter? General atmospheric circulation models rely on mathematical simplifications of gravity waves because the latitudinal and longitudinal grid size of the models is too large to include the individual gravity waves themselves. These models are used to estimate movement of greenhouse gases and anthropogenic pollutants, to provide climate-change scenarios, and to make ozone hole forecasts. Whether they produce differences between the Antarctic and Arctic middle atmospheres and whether those differences compare favourably to observational measurements is a stringent test of whether the gravity wave simulations are reliable. Their reliability is crucial for predicting climate change.

Maybe more important is that whatever processes can make the temperature in the Antarctic and Arctic differ may also affect the formation of NLC, PMC, and PMSE, which could be our most sensitive "litmus test" for global change. Antarctic measurements, by the difficult logistical constraints imposed, tend to be several years behind similar measurements in the Arctic but are an essential piece in the jigsaw to understand the Earth's atmosphere and how humans are altering planet Earth.

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See also **Climate Change; Ozone and the Polar Stratosphere; Polar Lows and Mesoscale Weather Systems**

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POLLUTION

Pollution is the undesirable change in physical, chemical, or biological characteristics of the environment as a consequence of human activities. It is caused by pollutants, which may be physical processes (such as light and heat), nonliving substances (such as oil and exhaust fumes), or living organisms (such as animals, plants, bacteria, and viruses). It may affect the health, survival, or activities of humans or other living organisms.

Antarctica is undoubtedly the least polluted of all the continents. This is because it has only a small and transient human population and has never been the site of industry, agriculture, or mining. Tourism and science are the main reasons for people's being in Antarctica and, with a few exceptions, the only buildings and infrastructure are there to support scientific research undertaken by the national Antarctic programs. Despite this, it is no longer a pristine environment. Many common pollutants of the modern world are now present in Antarctica. Some have been carried there by large-scale natural processes that move substances around the planet; others have been taken by people and discarded, spilt accidentally, or unavoidably released to the environment during normal use (such as exhaust fumes).

Worldwide, most research and regulatory attention has been directed towards pollution by substances (chemical pollution); however, pollution by physical processes and by living organisms is also of concern. In Antarctica, light pollution caused by station lighting can be detrimental to scientific studies, such as astronomical observations, that require dark conditions, and can cause bird deaths; similarly, broadcast radio waves can obscure the detection of radio signals from space. In general, physical pollution is transient. When the physical process, such as discharge of waste heat or light, is stopped, the problem goes away; for this reason these problems are generally managed within a station to avoid conflict by allocating areas or times for particular purposes. However, there are exceptions where physical pollution can cause lasting effects. If cooling water were pumped into an Antarctic lake it would disturb layering within the water that might have been established over millennia and disrupt the entire ecology of the lake. Similar harm can be caused by physical stirring created by rising air bubbles released by SCUBA divers in lakes.

Biological pollution (the introduction of nonnative species) has been recognised as a serious problem for many years and is the reason for quarantine regulations designed to limit the movement of undesirable living organisms around the world. Unlike physical or chemical pollution, which are generally limited in their extent and duration, biological pollution has the ability to spread and perpetuate itself by replication and for this reason has potentially the most damaging impact. Once a living organism has become established in a new environment it is very difficult to eradicate. Compared with other regions, the Antarctic continent is relatively free of introduced plants and animals, probably because climatic conditions there are so different. In contrast, the sub-Antarctic islands of the Southern Ocean have almost all been significantly changed by introduced species, including cattle, deer, rabbits, cats, and rats, as well as by many species of plants. Introduced species create a cascading series of impacts because of the interconnections in biological systems, for example, the introduction of grazing rabbits causes major changes to vegetation, which then has consequences for the rest of the ecosystem. Introduced species can also displace and out-compete native species. Heard Island is the only large sub-Antarctic island that has not been significantly polluted by introduced species.

Microorganisms such as bacteria, fungi, and viruses have inevitably been introduced to the Antarctic continent and, in localised areas around centres of human activity such as research stations, have become established. At the very least these have changed the microbial community structure of these locations; at the worst, introduced microbial pathogens could cause disease in the native flora and fauna of Antarctica. Introduced microorganisms could very seriously reduce the scientific value of some unique Antarctic environments. Subglacial lakes, such as Lake Vostok, have been isolated from the rest of the world under kilometres of ice for many millions of years and may contain remarkable information about the development of life on this planet. Very great care is necessary to ensure that the act of investigating these lakes does not irreversibly change them by the introduction of chemical or biological pollutants.

The chemical byproducts of modern living have now reached all corners of the world. Global distillation, the cycle of evaporation of pollutants in the warm parts of the planet and condensation in cooler places, is a natural process that selectively moves certain pollutants to polar regions. Transport by evaporation depends on three characteristics of the chemical: persistence—how long it survives in the environment without breaking down; volatility—how easily it evaporates; and water solubility—how easily it dissolves in water. Those most likely to reach the Antarctic by this mechanism are the persistent chemicals with intermediate volatility and intermediate water solubility. They can move great distances by a series of evaporation and condensation cycles or "hops." When they eventually reach a place where low temperatures are not sufficient for further evaporation, they remain and can accumulate. In Antarctica natural rates of breakdown are slower than elsewhere because the environment is not conducive to chemical degradation, which is accelerated by intense sun light, high microbial activity, and warm temperatures—conditions not found in Antarctica.

As a consequence of global distillation, manmade organic chemicals that would not be used in Antarctica, such as the pesticides lindane, toxaphene, and DDT and its derivatives (breakdown products) are found there and can accumulate in the Antarctic food chain. DDT was among the first persistent organic pollutant to be found in Antarctica. It is a synthetic chemical that does not occur naturally, so even very low concentrations are evidence that environmental contamination has occurred. In the 1960s it was found in some Antarctic marine species and since then it has been detected in seawater, sea ice, snow, and land ice. Levels of DDT in snow from increasing depths, representing different times in the past, are consistent with the period of high worldwide use of DDT in the 1970s and the subsequent reduction in use as the environmental problems it causes became apparent and controls on use were implemented. The data from the Antarctic are important as they provide a measure of the global "background" of contamination, uninfluenced by local sources. Overall the Antarctic data indicate that the global background for DDT has reduced one thousand–fold or more since the peak in the 1970s.

DDT has been detected in Antarctic plants and animals from both the land and sea. The highest concentrations are found in the fatty tissues of top predators such as seals and birds, particularly those that scavenge on the carcasses of other predators. There has been little reduction in tissue concentrations in seabirds since the 1970s peak, despite the reduction in worldwide use of DDT and the reduction in the physical environment, indicating that these chemicals are persistent within the food chain, especially in cold climates.

Other chemicals, such as PCBs (polychlorinated biphenyls, used for many industrial applications) and PAHs (polycyclic aromatic hydrocarbons, formed during incomplete combustion of fuel) can also be transported by global distillation and have been detected in Antarctica. However, these chemicals were also taken to Antarctica for particular purposes; for example, PCBs were commonly used as cooling oil in electrical transformers and as additives in paints to maintain flexibility. Because they were used locally, levels of these chemicals in Antarctica are less useful as indicators of global backgrounds than chemicals, such as insecticides, that were never used in Antarctica in large quantities.

In the Arctic, global distillation of chemicals such as PCBs contributes to pollution levels that threaten the health of indigenous human populations, particularly those that rely on local wildlife as an important component of their diet. Chemicals transported by this process are not a concern to human health in Antarctica because, with the exception of fishing, killing of native animals for food is not permitted below 60° S. However, these pollutants may have detrimental effects on Antarctic fauna and flora, although no direct evidence of harm has yet been reported.

The other major sources of pollution in Antarctica are the materials taken there to help people live and work. In the early days of expeditions to Antarctica there was no concept that people could harm the environment. Antarctica was seen as a vast and threatening place in which people needed to be protected from the environment rather than the other way round. Domestic waste was either burnt or disposed of in open rubbish tips just as at home, and support facilities were abandoned when expeditions left. The modern era of Antarctic science really began in 1957 during the International Geophysical Year, which stimulated a significant increase of scientific activity in Antarctica; many new stations were established but attitudes toward the environment continued as before. As a consequence many of the now-abandoned work facilities and waste-disposal sites originate from this period. Gradually, from the 1960s onwards, the world began to realise the consequences of environmental pollution, attitudes started to change, and this began to influence how things were done in Antarctica. During the 1980s, several nations stopped using open rubbish tips and began taking their waste away with them. The growing concern for environmental protection eventually led to agreement by Antarctic Treaty nations that Antarctica should be given comprehensive environmental protection.

The Protocol on Environmental Protection to the Antarctic Treaty was adopted in 1991 and has done much to reduce pollution from activities in Antarctica. This international agreement prohibits some potential pollutants' being taken to Antarctica and, for substances that are essential and cannot be banned, it has guidance on impact assessment, waste management, and emergency response in case of spills. Most wastes generated in Antarctica must now be returned to the country of origin, and disposal of waste to landfill and open burning are not permitted. The protocol requires that abandoned waste disposal sites be cleaned up so long as their removal does not create greater environmental impacts than leaving them where they are. Sewage from research stations must be treated before disposal and can be discharged to the sea only where it will disperse rapidly. The other major sources of pollution in Antarctica are accidental spills, routine operational discharges, such as exhaust emissions, and planned releases for scientific purposes. Recognising that major oil spills have the potential to cause widespread environmental damage, the protocol requires that countries have contingency plans for such environmental emergencies. In addition, the nations working in Antarctica have now agreed on an annex to the Protocol that will establish a financial liability for remediation of environmental damage arising from activities in Antarctica. Overall, the protocol has very successfully reversed the trend from rapid accumulation of pollution in Antarctica to slow removal and remediation.

The quantity of abandoned waste and contaminated soil in Antarctica has been estimated at 1–10 million m^3. This is not a lot compared to the quantity of pollution on the other continents, but it is significant in a place considered by many to be the last great wilderness. Importantly, the pollution is not spread equally over the entire area of Antarctica because most research stations and most human activity is concentrated on the small ice-free areas within 5 km of open coast, which represent only about 0.05% of the land area of Antarctica, or about 6,000 km^2. This narrow coastal strip is also the main habitat for many Antarctic animals and plants. To put the scale of cleanup in perspective, a recent operation using an ice-breaker with a large cargo capacity removed about 1000 m^3 from Australia's Casey Station during the 2003–2004 Antarctic summer season. Using the most optimistic estimate of the quantity of contaminated material in Antarctica, this represents only 1/1000th of the total.

Abandoned waste disposal sites in Antarctica typically contain a wide range of material similar to that in the municipal tip of any small country town. Food waste from kitchens, discarded clothes, and wood from packing crates contribute to the organic material. Organic material is not normally considered a pollutant because in other parts of the world it is plentiful in soils; however, most Antarctic soils and lakes have very low levels of organics and the addition of organic material can significantly change their ecology.

Many of the tips were burnt periodically to reduce their volume. Fuel was used to promote burning and as a result these tips contain residues of petroleum hydrocarbons and PAHs formed by incomplete combustion. The tips also contain waste oil, such as cooking oil and lubricants from vehicles and workshops. Together these form a complex mixture of hydrocarbons. Oily sheens are sometimes seen on water draining from tips during summer, indicating that contamination can spread. Hydrocarbons are known to cause a variety of harmful ecological effects, including smothering and oiling of feathers in extreme cases, direct toxicity to plants and animals, and subtle changes to soil microbial and physical processes.

Waste tips always contain a variety of metal objects, including tin cans, discarded machinery, batteries, copper wire and pipes, and much else. Chemicals discarded from photographic dark rooms and scientific laboratories may also contain metals. Together these become the source for a broad range of trace metals that could have harmful effects. Iron, lead, copper, tin, and zinc are the most common and others, such as arsenic, cadmium, chromium, silver, nickel, and mercury, are sometimes present in lower concentrations. Many metals are common components of natural minerals occurring in Antarctica and elsewhere. In their naturally occurring forms they are generally highly stable and tightly bound within the mineral matrix. In this form they are not readily available for uptake by plants and animals and do not cause ecological problems. The metals in the tip waste are in forms not normally found in the Antarctic environment and may be biologically available. High levels of anthropogenic (derived from human activity) metals are known to have a range of toxic effects.

Many of the waste tips are located in convenient gullies near the sea edge. This was because in the past, when the tips became too large or untidy, a common form of waste management was to push the rubbish on to the sea ice in early spring so that when the sea ice broke up in summer the waste would fall to the sea bed or would float away on pieces of sea ice. Although this was an acceptable solution in the past, it has now created further problems because rubbish and associated pollution is now spread widely on the sea bed rather than being contained at discrete sites.

A further problem with many of the sites used for waste disposal is that large quantities of water flow through them during the brief period in summer when temperatures are above freezing point and the snow melts. As a consequence, contaminants in the tips are not locked away, frozen in one location, but can be mobilised and transported to other places where they can have detrimental environmental effects. Because many of the tips are on the sea shore, the contaminants are carried by melt-streams into the marine environment, where they accumulate in sea-bed sediments, normally over a limited area. Research shows that they have a range of harmful effects on sea-bed animal and plant communities. The overall impact is similar to that caused by contaminants in other parts of the world; sea-bed communities impacted by pollution typically have lower species diversity than other comparable but unpolluted locations. They are often dominated by a few opportunist species able to thrive when competition is reduced because pollution-sensitive species have been eliminated.

Major accidental spills, such as fuel leaking from a damaged ship, are the most dramatic and possibly the most serious cause of pollution in Antarctica; fortunately this has occurred only rarely. Typically Antarctic activities depend on petroleum-based fuel for transport, power, and heating. The national Antarctic research programs together use about 100 million litres of fuel each year. This fuel has to be brought to Antarctica by ship and pumped from the ship to storage tanks, sometimes across several kilometres of open water, sea ice, and land. The harsh conditions of Antarctica undoubtedly add to the risks of spills during shipment, transfer, and storage.

Whenever fuel is carried in large quantities there is the risk of an oil spill, and ships in Antarctica face the additional hazards of navigating through sea ice. Vessels can become trapped by ice and in the past have been crushed and sunk to become a source of pollution as fuel and other substances leak. In recent times there has been only one major ship grounding in Antarctica resulting in the loss of large quantities of oil. In January 1989 *Bahia Paraiso* ran aground close to Palmer Station on the Antarctic Peninsula, releasing about 600,000 litres of diesel fuel. About 300 seabirds were killed by the direct effects of oil fouling and the spill may have contributed to reproductive failure of other birds. Oil also reached the sea bed, where many bottom-living plants and animals were affected. Because of their potential to create widespread pollution, many national Antarctic programs now have contingency plans for responding to oil spills.

Oil spills also occur on land. On several occasions storage tanks have leaked tens of thousands of litres of oil to the environment. If a tank develops a slow leak during winter when everything is covered in snow and ice, it may easily go unnoticed until the summer thaw. There are also many opportunities for smaller spills to occur. The soil around older vehicle workshops is characteristically contaminated with fuel and oil and, without special care, it is easy for small spills to occur during refuelling of vehicles and while transporting fuel to field parties at remote camps.

Pollution from fuel and oil is recognised as a problem in all parts of the world; however, in warmer regions natural processes such as evaporation, photodegradation (breakdown caused by exposure to light), and consumption by microbial organisms eventually degrade the complex molecules of oil, leaving simple and harmless components such as carbon dioxide and water. These processes require heat, light, available water, and nutrients, all of which may be limited in Antarctic soils. For this reason the natural breakdown of oil pollution takes considerably longer in Antarctica and as a consequence the environmental impacts of oil spills on land may last longer than elsewhere. Even in low temperatures light diesel fuels will evaporate quickly from the sea surface, especially under stormy conditions, so the use of dispersants is rarely recommended.

Some emissions, such as sewage effluent and exhaust, are accepted as unavoidable consequences of the human presence in Antarctica. However, measures are in place to reduce their environmental impacts. The protocol prohibits discharge of sewage to ice-free ground or to lakes because the addition of the large quantities of nutrients contained in sewage would significantly change the ecology of these nutrient-deficient biological systems. Discharge of treated effluent to the sea is allowed only where natural currents will permit rapid dispersal. The incineration of waste and the use of fuel in vehicles and generators both release combustion products to the atmosphere. Burning of waste is only permitted in incinerators designed to reduce harmful gases, and there are some attempts to use sustainable wind and solar power to reduce fuel consumption; however, in the foreseeable future, activities in Antarctica will continue to be dependent on burning fossil fuels.

Exhausts from incinerators and engines are complex mixtures of particles and gases; their nature depends on the temperature of incineration and type of material burnt, or the type of fuel, the efficiency of the engine, and how it is being used. Soot particles, sulphur, lead, and organic compounds are all present in exhaust and are detectable in snow at low concentrations around most Antarctic stations; however, no direct ecological effects have yet been reported. The most likely detrimental impact is to reduce the value of Antarctica as a "clean laboratory" for monitoring changes in background levels of some important indicators of global environmental quality, such as atmospheric lead.

Certain scientific activities also have the potential to create pollution, for example, radioisotopes are widely used by scientists as labels to trace natural processes and if handled carelessly could cause contamination. In Antarctica their use is very carefully controlled by the impact assessment process. Isotopes that decay to harmless elements quickly because of their short half-lives are preferable. Organic chemicals such as butyl acetate, kerosene, perchloroethylene, and trichloroethylene are used by scientists to assist with deep ice drilling. There are about 10 deep core holes in the ice of the Antarctic plateau with an average depth of about 2000 m and a diameter of 20 cm; together they contain about 600 m^3 of drilling fluid. Although present in large quantities, most are not an immediate environmental concern because they are locked in the ice and will remain there for many tens of thousands of years. However, they will eventually reach the coast and discharge into the sea. In contrast, the ice drilling to penetrate Lake Vostok is of very immediate concern. The drill hole contains about 60 tonnes of kerosene and freon drilling fluid, some of which could enter and contaminate the lake. The drilling fluid contains several species of bacteria, which could also contaminate the lake and reduce its value as a scientific resource.

The Antarctic Treaty has been very successful at keeping large quantities of radioactive material out of Antarctica. Nuclear testing and the disposal of nuclear waste are both banned in Antarctica. The US Antarctic program had a nuclear reactor at McMurdo Station during 1962–1972 that caused some radioactive contamination of soils before the reactor and the contaminated soils were removed. More recently, the protocol explicitly prohibits some other substances from being taken to Antarctica because they also pose a significant environmental risk; these include polychlorinated biphenyls (PCBs) and pesticides (unless required for scientific, medical, or hygiene purposes).

Despite the requirements of the protocol, high environmental standards are not always achieved and at many Antarctic research stations the standards reached would not satisfy domestic legislation. There are a number of reasons for this. Inefficient and outmoded technologies, such as for sewage treatment and incineration, continue to be used because of the cost and practical difficulties of replacement. In addition, the remoteness of Antarctica contributes to a sense of "out of sight, out of mind" and the difficult climatic conditions force compromise in the search for solutions to environmental problems. The root cause is the system of self-regulation that exists within many national Antarctic programs. In most countries, domestic environmental standards are enforced by legislation and litigation and the roles of proponent and regulator are kept very separate. This is not the case for most national Antarctic programs. The advantage of collocating responsibility for Antarctic operations and environmental management is that first-hand Antarctic experience is readily available; however, this comes at the cost of transparency of process and creates opportunities for conflict of interest.

In the populated parts of the world it is accepted that some contamination of the environment will occur, and guidelines are established to ensure that contaminants do not reach levels that become a threat to human health or to some valued component of the ecosystem. These levels vary depending on the setting; for example, land used for a children's playground would have more stringent standards than land used for heavy industry. Commonly, guidelines are based on toxicology—the study of the toxic effects of chemicals. Environmental standards have not yet been agreed on for Antarctica, but they will be required as targets for environmental remediation now that an effective liability annex to the protocol has been agreed on. It is often assumed that Antarctic animals and plants are more sensitive because they live in what we perceive as a harsh environment or because they have not previously been exposed to pollutants and so have not developed protective measures. In reality there is very little information available to assess the relative susceptibility of polar species (either Arctic or Antarctic) to pollutants. Very few have been used in toxicity tests and the few available results do not yet show a clear picture. However, some patterns are beginning to emerge; for example, the slow development time for some Antarctic species means they are in the sensitive early life stages for longer than similar species found elsewhere and for this reason may be affected by lower concentrations of pollutants. Ultimately people may decide that environmental guidelines based on toxicology are not stringent enough for Antarctica and that higher standards are required consistent with the Antarctic's role as a "clean laboratory" for monitoring the global background of pollution.

MARTIN RIDDLE

See also **Antarctic Treaty System; Biological Invasions; Coal, Oil, and Gas; Diseases, Wildlife; Health care and medicine; Heard Island and McDonald Islands; International Geophysical Year; Lake Vostok; Marine Debris; McMurdo Station; Microbiology; Operational Environmental Management; Protocol on Environmental Protection to the Antarctic Treaty; Soils; Subglacial Lakes; United States: Antarctic Program**

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POLLUTION LEVEL DETECTION FROM ANTARCTIC SNOW AND ICE

The large Antarctic ice cap has preserved accurately dated archives of global atmospheric pollution for heavy metals. Indeed, the snow layers deposited year after year contain heavy metals that have been emitted in midlatitude areas by human activities, and which were transported in the form of tiny particles to the Antarctic continent by winds. These particles are incorporated into the snow either during or after snow falls, and will be kept there virtually unaltered over long time periods. The snow layer deposited during a given year will be buried by the layer deposited during the following years and will ultimately become ice when it reaches a depth deeper than about 100 m. These accumulated layers will then constitute extremely interesting archives of atmospheric heavy metal pollution since they can be dated using a variety of techniques. To give an example, the snow that is presently at a depth of 10 meters at Dome C on the high East Antarctic plateau was deposited about 2 centuries ago. Its analysis will then give very precious information on the pollution of the atmosphere by heavy metals at that time. It should however be emphasized that these Antarctic archives mainly reflect the pollution emitted in the Southern Hemisphere, especially in South America and southern Africa. This is because pollution emitted in the Northern Hemisphere has difficulty penetrating into the Southern Hemisphere and reaching Antarctica.

Deciphering these frozen archives for heavy metals is unfortunately very difficult. This is because sampling has to be done in very inhospitable places with very low temperatures at high altitudes. Also, Antarctic snow is so clean that the utmost precaution must be taken by the researchers to collect the samples without contaminating them. One thousand tonnes of Antarctic snow typically contains no more than a few milligrams of lead. The analysis of such samples is also a real challenge. First of all the samples must be handled inside special laboratories similar to the clean rooms used in microelectronics to prevent any contamination. Also, incredibly sensitive analytical techniques are necessary to detect these very small amounts of metals. One of these techniques is inductively coupled plasma sector field mass spectrometry. Such a process can detect 10^{-13} g of cadmium in a 1-g sample in a few minutes.

Amongst the most spectacular results obtained so far is the reconstruction of past changes in lead pollution since the middle of the nineteeth century, which was achieved by analyzing a series of snow samples collected in Coats Land, on the Atlantic Ocean side of Antarctica (Planchon et al. 2003). They show that lead pollution of Antarctica started as early as the 1880s (i.e., before the conquest of the South Pole by Roald Amundsen). This early pollution was at least partially linked with nonferrous metal production activities in South America, southern Africa, and Australia. Another important contribution was from coal-powered ships that rounded Cape Horn between the Atlantic and Pacific oceans as well as whaling ships and shore-based stations along the Antarctic coast. This lead pollution then declined in the 1920s, especially because of the opening of the Panama Canal in 1914, which resulted in a pronounced decrease in ship traffic around the southern tip of South America. Lead pollution then increased again after World War II because of the very large rise in the use of leaded gasoline in various countries in the Southern Hemisphere, combined with the continuous increase in nonferrous metal production in South America, southern Africa, and Australia. Finally, lead concentrations strongly declined from the mid-1980s onwards, because of the fall in the use of leaded gasoline in modern cars.

Various other metals have also been determined in the Antarctic snow archives. The time series obtained show a clear increase in the concentrations of chromium, copper, zinc, silver, bismuth, and uranium during the twentieth century (Planchon et al. 2002). They are mainly linked with the emissions of these metals into the atmosphere from nonferrous metal mining and smelting in Chile, Peru, Zaire, Zambia, and Australia.

The general picture that is emerging from these studies is that the pollution of the atmosphere for heavy metals can be detected for many metals in Antarctica, that is, the most remote area of our planet. It means that atmospheric pollution for heavy metals is indeed global.

Scientists also analyze for heavy metals in very ancient Antarctic ice, whose age can reach more than 700,000 years. The goal is no longer to look at pollution, but rather to understand what the past natural concentrations of these metals in the atmosphere before any pollution were. Such information is necessary to put recent changes in a proper perspective (Hong et al. 2003).

Highly interesting data have also been obtained by analyzing heavy metals in the dated snow and ice layers deposited in Greenland, the Northern Hemisphere's counterpart to Antarctica. Greenland provides us with a good view of the history of heavy-metal pollution in the Northern Hemisphere. Amongst the most interesting results obtained in Greenland is the evidence of early pollution of the atmosphere of the Northern Hemisphere for lead and copper two millennia ago at the height of the Roman Empire (Hong et al. 1994, 1996). The determination of platinum, palladium, and rhodium in Greenland snow dated from the last few decades also showed evidence of large-scale pollution of the Northern Hemisphere for these metals linked with the ever-increasing use of automobile catalytic converters (Barbante et al. 2001).

Various studies are currently ongoing, especially for metals such as mercury.

Claude Boutron and Carlo Barbante

See also **Air-Borne Ice; Amundsen, Roald; Climate Change; Earth System, Antarctica as Part of; Firn Compaction; Ice Chemistry; Ice–Atmosphere Interaction and Near-Surface Processes; Ice Core Analysis and Dating Techniques; Isotopes in Ice; Paleoclimatology; Precipitation; Snow Biogenic Processes; Snow Chemistry; Snow Post-Depositional Processes; Volcanoes**

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POLYNYAS AND LEADS IN THE SOUTHERN OCEAN

The sea ice surrounding Antarctica and covering much of the Southern Ocean is far from homogeneous; instead it is littered with patches of open water and cracks. Larger, persistent areas of open water within the sea ice pack are called polynyas (a word of Russian origin), while linear cracks in the sea ice are called leads. These areas of open water have an important impact on both the ocean and the atmosphere, as they enhance energy and moisture exchange between the two. The elevated heat and moisture fluxes within polynyas and leads are signalled by what Apsley Cherry-Gerrard called "frost smoke"—a condensation fog that occurs a few metres above the surface as the air becomes saturated and water vapour condenses out. The impression one gets is of the ocean boiling like a kettle; given the enormous air–sea temperature differences (perhaps 30°C–40°C), the physics is not that different. Another signal of polynyas and leads is the dark "water sky" reflections that they cast upwards onto any low-level cloud. In the featureless, often all-white seascape of the sea ice pack, these water skies stand out. To the present day they provide a navigational beacon for ships crossing the sea ice pack, indicating where the easy passages of open-water areas are situated.

Polynyas are typically rectangular or elliptical in shape and occur regularly in the same location. They can be classified by location as either coastal (or shelf-water) polynyas if they are over the continental shelves, or as open-ocean (or deep-water) polynyas if they are located farther offshore. Polynyas are typically tens to hundreds of kilometres in scale. Leads are typically much narrower across, from tens of metres to a few kilometres, but can be up to hundreds of kilometres long.

The topological distinction between polynyas and leads is reinforced by a causal distinction. Polynyas are formed by a coherent external forcing mechanism that either moves or melts the sea ice, for example, advection by strong winds and ocean currents or melting by warm water. In contrast, leads are formed by an internal deformation of the sea-ice pack, where cracks develop somewhat at random as a result of sea ice dynamics. This means polynyas tend to occur in fixed and predictable locations, for example, tied to particular parts of the coastline or to seamounts, whereas leads occur seemingly at random as the sea ice cover is shattered by internal stresses. Of course, the sea ice is also externally forced by wind stress, ocean currents, and tides.

Coastal polynyas generally form when strong persistent winds blow the sea ice offshore. Hence they tend to be located on coastlines prone to persistent offshore winds, often topographically driven, such as katabatic winds or barrier winds. For example, there are recurrent coastal polynyas off the Ronne Ice Shelf, the Ross Ice Shelf, and the Mertz Glacier, and in Terra Nova Bay. As sea ice is advected offshore, an area of near-freezing water opens up and fluxes of heat from the relatively warm water into the cold atmosphere result in the formation of new sea ice. The latent heat that is released during this freezing means these polynyas are traditionally known as "latent heat" polynyas, although in this case "wind-driven" would be a better description, as this is what drives their life cycle.

During an episode of relatively strong offshore winds, a coastal polynya will act as a site of enhanced ice production. In particular, millimetre-scale frazil ice crystals are formed throughout the water column. The frazil ice rises and is collected into slurries, often organised into a downwind-oriented band by circulations in the surface waters called Langmuir circulations. These slurries, also known as "grease ice," are on the order of 10 cm deep, and damp the surface waves. The frazil and grease ice are advected downwind, with this mixture eventually piling up against the downwind consolidated ice pack. During this advection, the ice will coalesce and freeze into a more solid ice covering, but also be broken into metre-sized discs, or "pancake ice," through swell and wave action. Coastal polynyas have been dubbed "ice factories," producing ten times more than the average sea ice thickness around Antarctica. Once the winds drop, offshore ice advection slows, and the new ice that is being formed will gradually seal over the polynya. The balance between ice advection and ice production determines the width of coastal polynyas. For the same wind speed, lower air temperatures lead to higher ice production and so narrower polynyas, while higher air temperatures lead to lower ice production and so wider polynyas.

Open-ocean polynyas form over deeper waters, that is, off the continental shelves, although they are often associated with submarine mountains. The most intriguing example was the "Weddell Sea Polynya" of 1974–1976, when an area the size of France remained largely ice free for three consecutive winters, yet this has not occurred to the same extent since. It was only observed by the very new (at that time) satellite-borne passive microwave remote sensors. It originally formed over the Maud Rise seamount (65° S, 6° E), but moved westwards during the 3-year period. There are also recurrent open-ocean polynyas over Maud Rise and in the Cosmonaut Sea. Open-ocean polynyas are generally formed by an upwelling of warmer waters from depth, triggered by submarine topography, weak vertical stratification, eddy formation, tidal motion, or some combination of factors—indeed, their formation is still a matter of debate. The warm waters melt existing sea ice and prevent new ice from forming, thus keeping the polynya open and giving rise to the term "sensible heat" polynyas. They are to some degree self-sustaining, as the surface waters of the polynya are cooled by the atmosphere, leading to sinking and turbulent convection. The convection will cease as the cooling decreases in spring, or it can be shut off earlier by a fresh-water cap formed by lateral advection or melting and precipitation.

Most coastal polynyas tend to be wind-driven, or current-driven, while most open-ocean polynyas tend to be thermally driven. However, some polynyas have combinations of these mechanisms; for example, the Ross Ice Shelf polynya is primarily controlled by synoptic-scale weather systems forcing ice divergence in front of the ice shelf, but an upwelling of warm water also contributes to this region's being prone to thin ice and open-water areas.

Radiation is also important in controlling the surface energy balance of polynyas and leads. During winter, the relatively warm surface means a relatively large upward longwave (infrared) radiative flux, contributing to a cooling of the ocean. During spring and summer, polynyas and leads absorb more shortwave (solar) radiation due to their lower albedos, and so contribute to an enhanced warming of the ocean, compared to the surrounding ice-covered areas.

Polynyas and leads are significant for the ocean, the atmosphere, human activities, and biology. For the ocean, their importance lies in their ability to change water properties. The role of coastal polynyas as zones of enhanced sea ice production means they are sources of salt (as some salt is rejected as sea water freezes) and so act to make the surface waters more saline and dense. Over continental shelves such as in the southern Weddell Sea, this creates High Salinity Shelf Water, which sinks and then predominantly circulates underneath, and interacts with, the Ronne-Filchner Ice Shelf, eventually leaving this cavity as Ice Shelf Water. This then mixes with other water masses, ending up leaving the continental shelf to form Antarctic Bottom Water—the deepest water mass of the world's oceans. The rate of ice formation within coastal polynyas is a key component in this chain of events and so plays a role in forcing the ocean's thermohaline circulation. Open-ocean polynyas also create dense water masses through a cooling throughout the depth of the ocean by open-ocean convection (i.e., a cooling into the atmosphere). Water mass transformations will also be enhanced by elevated cooling and brine rejection under leads; however, due to their more random location, such transformations are not as concentrated into particular locations and so perhaps less directly relevant for ocean circulation.

During winter, exposing areas of relatively warm open water also has a dramatic impact on the atmosphere, acting as a source of heat and moisture at the surface. Polynyas and leads act to warm and moisten the atmosphere and induce a convective well-mixed boundary layer. The convective circulation will be of a similar horizontal scale to the heating source (i.e., the polynya or lead). So polynya-induced atmospheric modifications can be tens to hundreds of kilometres in scale, and reach thousands of metres in height. Polynyas act through warming and, in general, accelerating the atmospheric boundary layer to develop mesoscale cyclones, enhance synoptic-scale cyclones, and accelerate katabatic flows through an "ice-breeze" mechanism. In contrast, lead-induced atmospheric circulations will tend to be much smaller, only hundreds to thousands of metres across and generally limited to tens to hundreds of metres vertically.

In addition to local changes to the atmospheric circulation, the integrated affect of polynyas and leads is to enhance the transfer of heat and moisture from the ocean to the atmosphere. For much of the year, a great deal of the Southern Ocean is insulated from the atmosphere by sea ice. Any areas of open water break through this insulation. So within polynyas and leads the air-sea turbulent heat exchange can be up to two orders of magnitude higher than over the surrounding sea ice. Therefore, although the areal coverage of polynyas and leads is small, only a small percent of the total area covered by sea ice, their contribution to warming the atmosphere and cooling the ocean is large.

As mentioned earlier, polynyas and leads provide natural routes for ships crossing the ice-covered seas. In addition to aiding immediate navigational choices, the larger predictable areas of open water or thin ice have for years been used as preferred shipping lanes for the resupply of Antarctic bases. For example, during the resupply of the British Antarctic Survey's Halley Research Station, on the Brunt Ice Shelf, in the southeastern Weddell Sea, the ships always curve well to the east of a straight line from the Falkland Islands, or South Georgia, to pass through the recurrent polynyas and thin ice in the vicinity of Maud Rise around 0°–5° E.

Polynyas and leads are havens of biological and wildlife activity. Sea mammals need breathing holes in the sea ice, so they tend to concentrate in polynyas, while during summer, polynyas' lower ice concentration means an earlier melt back, a larger annual absorption of solar radiation (due to a lower albedo), and so higher primary productivity. This attracts krill and therefore penguins, birdlife, and sea mammals to these areas.

Numerous mathematical models of individual polynyas and leads have been developed, to examine polynya dynamics, sea ice dynamics, and the impact of polynyas and leads on the circulation of the atmosphere and the ocean. It is now realised that some representation of polynyas and leads is also required in large-scale climate models, but due to their relatively small size their primary effects—heating the atmosphere and cooling the ocean—have to be represented in a simplified manner. Given the limited observations and developing understanding of the physics of polynyas and leads, their representation in climate models is presently crude and very much an area of active research.

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See also **Amundsen Sea, Oceanography of; Antarctic Bottom Water; Atmospheric Boundary Layer; Climate Modelling; Polar Lows and Mesoscale Weather Systems; Remote Sensing; Ross Sea, Oceanography of; Sea Ice: Microbial Communities and Primary Production; Sea Ice: Types and Formation; Sea Ice, Weather, and Climate; Synoptic-Scale Weather Systems, Fronts and Jets; Thermohaline and Wind-Driven Circulations in the Southern Ocean; Weddell Sea, Oceanography of; Wind**

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PONIES AND MULES

Shackleton's British Antarctic Expedition

With hindsight it is easy to say that the use of ponies as draught animals in the Antarctic was a poor choice. However, at the time Ernest Shackleton first took ponies to the continent on his British Antarctic Expedition (1907–1909), there were plausible reasons for the decision. Shackleton believed that the dogs that had gone south across the Ross Ice Shelf with Robert Falcon Scott, Edward Wilson, and him on the British National Antarctic Expedition in 1902–1903 had failed. That the three men had no previous experiences working with or driving dogs, and had therefore not truly known how to do so, did not seem to enter into his assessment.

Shackleton was told of the advantages of ponies by Albert Armitage, second-in-command of Scott's expedition, who had also been a member of the Jackson-Harmsworth Expedition to Franz Josef Land in 1894–1897. So when he considered modes of transport for his own expedition, Shackleton consulted Frederick Jackson, the leader of that earlier expedition. Jackson felt the ponies he had used had been an unqualified success, and he pointed out that ponies had been used extensively in other cold northern lands, as indeed they had recently in the Russo-Japanese War. There was also a feeling that ponies would withstand the cold better than dogs, drag heavier loads on less food, and provide good meat for humans.

Shackleton arranged for the purchase of fifteen Manchurian ponies from northern China. They were each approximately 14 hands in height and estimated to be 14–17 years old. From China they were taken by ship to Lyttelton, New Zealand, where they were quarantined on Quail Island. W. H. Tubman, a local horse trainer, and Dr. Alistair Mackey of the expedition looked after the ponies, which had the reputation of being wild and difficult to manage. They broke them in to the practice of hauling sledges. However, *Nimrod,* the expedition ship, was so small that only ten could be taken south. Their food consisted of 20 tons of maize, 1000 pounds of Maujee ration, known as "Equine pemmican" (dried beef, carrots, milk, currants, and sugar), and 10 tons of compressed fodder of oats, bran, and chaff obtained in Australia.

Before Shackleton's party was able to land, two of the ponies had been destroyed. The others became the first to be landed in the Antarctic on February 5, 1908, and were soon being used to help haul materials as the ship was unloaded. A special shelter for the ponies was built against the hut using maize bales and canvas tarpaulin for the roof. The snow that piled up around it gave further insulation. Within the first month of being at Cape Royds, four more of the ponies died from eating either large quantities of salt-covered sand or corrosive materials that had been stored nearby.

Only four ponies—Quan, Socks, Grisi, and Chinaman—were left to face the winter. Quan was a trouble-maker, biting and kicking and making a din at night, but he nevertheless became a favourite. Grisi was aggressive toward the other ponies. There was a night light in the "stable," and a nightwatchman inspected it every 2 hours. The shelter was shared with the dogs.

With only four ponies left, Shackleton reduced his southern party from six to four men, and they left Cape Royds on October 29 to try to reach the South Pole. From the start, the ponies proved to be problematic. Within an hour of their departure Socks went lame, and then at lunch Grisi kicked out, catching

Jameson Adams 3 inches below the knee and exposing the bone. It was soon shown that the poor creatures simply were not appropriate for travel in a glacial environment. They constantly broke through the crust of snow that dogs would have lightly run across. They were not designed for the cold weather, as they sweated throughout their bodies and had hides that helped dissipate heat rather than retain it, which meant that when they had to bivouac outside each night, exposed to the bitter cold and wind, the men had to build snow walls to protect them from the wind, to rub them down, and to cover them with blankets. Then in the morning they had to scrape the snow off their hooves. Moreover, the ponies' food was excessively bulky.

The ponies soon began to wear down, and on November 21 Chinaman was put down. A week later it was Grisi's turn, and on December 1 Quan was killed after breaking down in harness. Only Socks was left, and on December 7, while the party was slowly making its way up the Beardmore Glacier, he went down a deep crevasse, almost pulling Frank Wild in with him, and depriving the men of what would have been an important supply of meat. So ended the first use of ponies in the Antarctic, but Shackleton's subsequent success in reaching a point only 97 miles from the Pole left open the question of whether, had Socks not been lost as both a puller and a food supply, Shackleton and his party might have been the first to reach the South Pole.

Scott's Last Expedition

When Scott planned his second Antarctic expedition, he included the use of several modes of transport, including ponies, dogs, and motor sledges. Although he has been criticized for bringing ponies, it must be remembered that Shackleton had made a remarkable journey with them, so it was logical for Scott to use them as well.

Scott sent his brother-in-law, Wilfred Bruce, to obtain ponies from Harbin in northern China. He was assisted by the Russian jockey Anton Omelchenko, who was hired to look after them on the journey. Money donated by schools, clubs, and individuals paid for the 20 animals selected, 18 Manchurian and 2 Siberian ponies 14–15 hands high. At Vladivostok, Bruce and Omelchenko met up with Cecil Meares, Dmitri Gerof, and their Siberian huskies. The party traveled to Lyttleton via Kobe, Japan, and Australia, spending 52 days aboard ship before reaching Quail Island.

Captain L. E. G. Oates, who was in charge of the ponies, had had extensive experience with horses in England, during the Boer war, and in India. He purchased extra fodder himself for the ponies and had it put aboard *Terra Nova*. The ponies were reported to be rather old and not in tip-top condition. A storm on the way south accounted for the loss of two of the ponies. However, once on land the ponies were staked on snow away from the volcanic ash and sand that had proven fatal for Shackleton's animals.

Much else had been learnt from Shackleton's experiences, and the ponies' legs were protected from the ice with puttees, thick rugs were worn, and snow shelters were built at each stop. However, they still suffered from thinning coats, which might have been due to their transfer from the Northern Hemisphere and subsequent lack of time for winter coats to grow.

The first autumn depot-laying journeys were disastrous. Six of eight ponies were lost, three due to poor condition, others on an unfortunate incident on the sea ice near Hut Point, and Hackenschmidt died on a separate journey.

Despite some medical problems, the ponies flourished under Oates' care, and there were thirteen ready for the main sledging journey in the spring, the start of which, unfortunately, was delayed to allow for better conditions for the ponies. As on Shackleton's expedition, the ponies worked well at the beginning of the journey, pulling loads in excess of 500 lbs. Soft, deep snow, blizzards, and cold took their toll, however, and Jehu was shot on November 24 and three more in the first days of December. The long blizzard, starting on December 5, was as hard on the ponies as on the men. The relationship between the men and ponies was shown when Edward Wilson fed Noddy his precious biscuits, despite knowing his equine friend was due to be shot the next day. On December 9, the five remaining ponies—Snippits, Jimmy Pigg, Nobby, Bones, and Snatcher—were destroyed as their fodder had run out and the men had reached the edge of the Beardmore Glacier.

Mules

Before Scott left New Zealand in 1910, he and Oates had decided to obtain mules for their second season in the Antarctic. They wanted trained Indian mules, which were donated by the Indian government. A small group of 7-year-olds standing about 13 hands were chosen. Much thought was given to their preparation for the Antarctic. They were trained at high altitude and a special "rocking box" was used to simulate the movement of the ship. The idea was to strengthen their muscles so that the journey to New Zealand and then on to the Antarctic would be less of an ordeal than it had been for the ponies.

The mules arrived in New Zealand in September 1911, equipped with rugs and leg coverings lined with thick felt and laced with canvas. These were manufactured at the Elgin Mills, Cawnpore. Eye shades, head pieces, and tethering chains covered with thick felt and leather showed the care taken in their preparation.

James Robert Dennistoun, a New Zealand farmer and mountaineer, looked after them on Quail Island. Good horse boxes were provided for *Terra Nova* and placed facing inwards. Eyebolts were fixed to these temporary stables so that a fallen mule could be winched up. On the voyage south, the mules received three feeds a day and plenty of water.

Apsley Cherry-Garrard and Tom Lashly took charge of the mules in the Antarctic, but each was assigned to a leader for field work: Khan Sahib to Edward Nelson, Lal Khan to Tryggve Gran, Pyaree to Lashly, Rani to Tom Crean, Gulab to Thomas Williamson, Begum to Patrick Keohane, and Abdullah to F. J. Hooper.

The mules were part of the search party that found the bodies of Scott, Wilson, and Birdie Bowers on the Ross Ice Shelf on November 11. The next day, Lal Khan and Khan Sahib were shot due to poor condition. Bad weather conditions on the return contributed to the deterioration of Begum and Abdullah, and they were destroyed. Finally, the remaining three mules were shot at Cape Evans just prior to the party's final departure from the Antarctic in January 1913.

JOHN KILLINGBECK

See also **British Antarctic *(Nimrod)* Expedition (1907–1909); British Antarctic *(Terra Nova)* Expedition (1910–1913); British National Antarctic *(Discovery)* Expedition (1901–1904); Oates, Lawrence Edward Grace; Ross Ice Shelf; Scott, Robert Falcon; Shackleton, Ernest; Wild, Frank; Wilson, Edward**

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PRECIPITATION

The Antarctic is generally regarded as the "White Desert," which implies a significant aridity over the continent as a whole, where it averages 20 cm per annum water equivalent (w.e.) or 50 cm snow. However, it is clear that there are considerable spatial and temporal variations in precipitation over a continent some 13 million km^2 in size and ranging in altitude from low-lying coasts to above 4000 m above sea mean level. It should be noted that *in situ* measurements of Antarctic precipitation are extremely limited, due to the imprecise nature of snow-gauge data. More reliable precipitation trends are associated with snow stake surveys and related pit excavations, where snow densities and water equivalent values can be determined. Also, the analysis of annual accumulation layers in ice cores has provided useful data, and satellite observations are used to determine ice-thickness changes at a variety of scales.

The measuring stations are only sparsely distributed over the continent and are concentrated along the coast, where local orographic controls are influential (e.g., at Law Dome, Wilkes Land). Furthermore, their observation record is relatively short and has been interrupted by station closures and transfers. Climate models (e.g., the Regional Atmospheric Climate Model [RACMO]) are used to reveal precipitation trends but need verification by additional measurements and/or ice core data.

Precipitation occurs when saturated air is forced to rise by free or mechanical convection, which cools adiabatically and condenses. The resultant hydrometeors eventually exceed their terminal velocity through a number of growth mechanisms, especially the Bergeron-Findeisen process associated with the coexistence of supercooled droplets and ice crystals. This results in precipitation that in Antarctica is mostly in a solid form, although on the coast, up to 1 cm rain per annum is recorded, whereas the northern parts of the Antarctic Peninsula receive up to 10 cm rain per annum. Mechanical or forced convection dominates vertical air movement in Antarctica, since the lapse-rate steepening requirement for free convection is negated by the persistent temperature inversion. It is mainly associated with orographic uplift and frontal displacement combined with the mass convergence of air in low-pressure systems. These convective controls dominate the distribution of precipitation in Antarctica. For example, the flat inland ice domes of East Antarctica are arid since precipitation is less than 10 cm w.e. per annum. This true polar desert is remote from coastal depressions/cyclones and orographic enhancement and is influenced more by the persistent glacial anticyclone and associated air subsidence and katabatic air flow.

Consequently, some 90% of the precipitation that occurs above 3 km on the Antarctic plateau is associated with an unusually strong advection of maritime air above the stable surface inversion. This invading airstream cools adiabatically and becomes supersaturated with ice crystals, which are precipitated on to the plateau surface from clear skies. Conversely, coastal Antarctica is directly influenced by migratory depressions and fronts. On the advancing edge of the low, the northerly Southern Maritime airstream has a high moisture content, which, coupled with dynamic and frontal uplift, accentuates precipitation along the coasts (exceeding 40 cm w.e. per annum) and Antarctic Peninsula. Here, precipitation exceeds 60 cm w.e. per annum and approaches 150 cm in some sources. Orographic enhancement is evident along the windward slopes of the peninsula, Marie Byrd Land, and the Transantarctic Mountains, where precipitation is concentrated. However, the ice-free Dry Valleys (so called oases), such as the Wright Valley in Victoria Land, are maintained by a strong snow-shadow effect, excessive deflation, and sublimation in this windy and dry environment.

The strong orographic control on Antarctic precipitation is confirmed by climate/atmospheric modelling. Over the Antarctic Peninsula, maximum precipitation exceeds 200 cm w.e. per annum on the northwest slopes, compared with less than 50 cm in the snow shadow of the eastern slopes. The modelling also confirmed very strong windward and snow-shadow effects on a local scale in coastal East Antarctica, where topographic promontories block the circumpolar easterlies. For example, Law Dome in Wilkes Land had strong east-to-west precipitation gradients with distinctive snow-shadow effects on the leeward slopes.

Temporal precipitation trends in Antarctica appear to be related to the strengthening of the circumpolar vortex in the Southern Hemisphere Annual Mode (SAM) or Antarctic Oscillation (AAO) in the summer and autumn/fall seasons in recent decades. The resultant zonal/westerly air flow advects warm moist maritime airstreams over the Antarctic Peninsula. A strong circumpolar vortex (i.e., high AAO index) is responsible for significant changes in precipitation (reaching 99% confidence levels). For example, increases up to 30% are found over the warming western Antarctic Peninsula, while the cooling western Marie Byrd Land and East Antarctic show decreases of a similar magnitude. However, in the snow shadow zone of the eastern side of the Antarctic Peninsula, precipitation patterns remain constant.

RUSSELL THOMPSON

See also **Antarctic: Definitions and Boundaries; Antarctic Peninsula; Climate; Climate Modelling; Clouds; Dry Valleys; Meteorological Observing; Oases**

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PRIESTLEY, RAYMOND

Raymond Edward Priestley, Kt, MC, DSc, MA, was born on July 20, 1886, at Tewkesbury in the west of England, the second son of the headmaster of the local grammar school.

It was through a chance encounter in 1907 at University College, Bristol, where he was completing the second year of a geological degree, that he was recommended for Ernest Shackleton's British Antarctic Expedition. A scientist who had been south with the *Challenger* Expedition (1872–1876), and was then working at Bristol Museum, had just declined an invitation to join Shackleton when Priestley's older brother walked in. It was suggested to him that the younger Priestley might be interested in going as the expedition's geologist. He was. A casual interview in London followed, and soon thereafter he was set to work sorting out equipment.

He was curious to know why he had been chosen instead of any of the dozen well-qualified applicants, and was told later by Jameson Boyd ("Bill") Adams that the other recruits were "real hard nuts" and that Shackleton had commented "Well! Anyhow I can manage that fellow!" Thus it was that Priestley got his first chance in scientific life. But Shackleton was a shrewd judge of character and the youthful, quiet, conscientious, hard-working Priestley proved to be one of the most useful and best-liked of the expedition members.

On arrival at McMurdo Sound in January 1908, he was incapacitated by an old knee injury and was temporarily relegated to caring for the eight ponies, but was soon working with Professor T. W. Edgeworth David of Sydney University, a world-renowned geologist who became his mentor and life-long friend. It was typical of Priestley that when David officially joined the expedition after it had sailed—thereby replacing Priestley as head geologist—rather than being upset by an effective demotion, he was enormously excited and positive because it would mean better scientific results for the expedition.

In between transport rehearsals, with ponies, man-hauling, and an Arrol-Johnston car, David, Priestley, and Douglas Mawson—another Australian geologist who had actually been appointed as the expedition physicist—collected as many geological specimens as far afield as possible. In March 1908, David led the first ascent of the active volcano Mount Erebus (12,450 feet/3795 m), conducting observations and collecting samples at the craters. (Priestley led a second ascent in 1912, during Robert Falcon Scott's *Terra Nova* expedition.) That winter, Priestley also took over the biological dredging while the biologist James Murray was unwell.

Shackleton's main summer journey was a bid to reach the South Pole while a second party, led by David, located the South Magnetic Pole. Having helped lay depots for both polar parties, Priestley, Sir Philip Brocklehurst, and Bertram Armytage began geological work at "Dry Valley" and later the Ferrar Glacier. Very few fossils and no valuable minerals were found, but their work was nevertheless of great interest, and they corrected the maps made on Scott's first expedition.

The expedition returned to New Zealand in March 1909, and Priestley eventually joined David in Australia to work on their rock collections. A monograph, published jointly, was the first attempt to elucidate the structural geology of South Victoria Land and was part of Priestley's work for a research degree. Another important result came by chance when on the way home he just managed to rescue a piece of limestone that Frank Wild had collected from the Beardmore Glacier and was about to give away. Thin sections revealed that it was full of fragments of *Archaeocyathus,* a common ancestor of sponges and corals, the only recognisable fossil collected on the expedition. It was eventually the subject of a memoir by Professor Griffith Taylor.

In December 1910, one of Scott's recruits for the *Terra Nova* expedition became ill and Priestley was asked to replace him. Once more he left university without a degree and, according to his diary, "So began the second chapter of adventure, twice as long, twice as exciting and twice as profitable...."

Back in the Antarctic in January 1911, Priestley was assigned to Victor Campbell's Northern Party, which wintered at Cape Adare and was later stranded at Evans Cove when *Terra Nova* failed to relieve them. The six men spent an appalling winter in a small ice cave on Inexpressible Island, with only 6 weeks' planned provisions and a small quantity of seal and penguin meat, using blubber for light and heat. It is a measure of the esteem in which the ever-cheerful and competent Priestley was held that he was put in charge of the rations. In the spring, half-starved, with worn clothes and tents torn to ribbons, they struggled back to base at Cape Evans, where they learnt of the loss of Scott's Pole party. Some of their own notes and specimens survived and were later worked on. Samples from Priestley Glacier contained pieces of a fossil tree, later named *Antarcticoxylon Priestleyi,* evidence of a subequatorial past.

Priestley received a Polar Medal and Clasp for his Antarctic service. After distinguished service in France during World War I, for which he was awarded the Military Cross, he was seconded to the War Office to write official histories. He returned to Cambridge in 1920, where he at last gained his degree and was elected Fellow of Clare College. Frank Debenham, Griffith Taylor, and Charles Wright were also in Cambridge working on expedition reports, and Priestley became involved with Debenham in the founding of the Scott Polar Research Institute.

In 1934, Priestley was appointed Registrar General of the Faculties, the first of his many academic posts, and a year later became Vice-Chancellor of Melbourne University. 1n 1938, he was appointed Principal and Vice-Chancellor of Birmingham University, where he remained until his retirement in 1952, serving on numerous committees and being made a member of the Asquith Commission on Higher Education in the Colonies. He was knighted in 1948 for his services to education.

He was appointed chairman of the Royal Commission on the Civil Service (1953–1955), president of the British Association for the Advancement of Science (1956), a member of the Royal Society's Antarctic Committee (1955–1958), president of the Royal Geographical Society (1961–1963), and acting director of the Falkland Islands Dependencies Survey, later renamed British Antarctic Survey (1955–1958). To all of these he bought wisdom, experience, and energy.

In 1957, Priestley accompanied H. R. H. the Duke of Edinburgh on a tour of the British Antarctic bases, and he was a guest of Operation Deep Freeze IV in 1958–1959. The latter enabled him to revisit the scenes of his early labors.

In 1915, Priestley married Phyllis Mary Boyd, a New Zealander, by whom he had two daughters. Lady Priestley died in 1961 and Sir Raymond on June 24, 1974.

ANN TODD

See also **British Antarctic *(Nimrod)* Expedition (1907–1909); British Antarctic *(Terra Nova)* Expedition (1910–1913); British Antarctic *(Terra Nova)* Expedition, Northern Party; British Antarctic Survey; *Challenger* Expedition (1872–1876); Commonwealth Trans-Antarctic Expedition (1955–1958); David, T. W. Edgeworth; Debenham, Frank; History of Antarctic Science; Scott Polar Research Institute; Shackleton, Ernest**

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PRINCE EDWARD ISLANDS

The Prince Edward Islands are an archipelago of two small islands located at 46°54′ S, 37°45′ E. Marion Island rises to 1230 m and has a surface area of approximately 290 km^2, whilst the smaller Prince Edward Island (45 km^2) lies 22 km northeast of Marion Island and rises to 672 m. The islands represent the peaks of two coalescing shield volcanoes, with an oldest recorded date of 450 ka for rocks on Marion Island. The islands are entirely oceanic in origin and their lavas (Aa, pahoehoe, and block lavas) are basaltic, with pyroxene, olivine, and feldspar predominating. The last eruptions were small, nonpyroclastic outflows in 2004 and 1980, although scoria cones across the islands testify to earlier more explosive events. Typically, the lavas are divided into older "grey" (276–100 ka) and younger "black" (15 ka to 400 years) lavas, although the distinction is often not clear. Volcanism is thought to have been initiated by isostatic adjustment, especially following deglaciation at the end of the last glacial maximum.

Marion Island shows signs of five to eight glaciations during the Quaternary. Landforms such as erratics, striae, and moraines all testify to substantial glacial activity. By contrast, there is little evidence for glaciation on Prince Edward Island. Temperatures during the last glacial maximum were 2°C–4°C lower than at present and the whole of Marion Island may have been covered by ice, with the exception of some areas such as Feldmark Plateau and parts of Long Ridge. The young landscape of the islands is highly dynamic. Important features include stone stripes that are a consequence of interactions between wind and surface cooling, solifluction terraces, especially those associated with the cushion-plant *Azorella selago,* surficial creep by needle ice, frost heave, and lens formation. Permafrost occurs at altitudes above 1000 m, but is rapidly degrading as a consequence of current warming. The small stationary glacier between the peaks is likewise rapidly declining in extent.

The islands have a cool oceanic climate with little seasonal or diurnal variation. Mean annual temperature is 6.2°C, and total precipitation is c. 2000 mm. The winds are typically westerly or northwesterly, often reaching gale force. Cloud cover is high and snow may fall at any time of the year, although it is more common in winter with the snow line descending to c. 500 m. During summer the peaks may be almost entirely free of snow. The weather is a consequence of periodic cyclones that bring warm, northwesterly winds and rain to the islands. As these cold fronts pass, the winds switches to the southwest, bringing cold, clear-sky conditions associated with snow and graupel showers. Microclimates are typically warmer, with the western sides of the island also warmer and moister than the eastern. During the past 50 years, conditions have changed substantially at the islands. Mean annual temperature has increased by slightly more than 1°C, annual rainfall has declined by 600 mm, and the frequency of easterly winds and sunny days has increased. There has also been a southward shift in the sub-Antarctic front, associated with warmer sea temperatures and a planktonic biota more typical of warm water bodies.

Biogeographically, both the marine and terrestrial components of the biota have their strongest relationships with other South Indian Ocean Province islands, such as Îles Crozet and Îles Kerguelen.

However, weaker relationships with the Antarctic, southern continents, and Africa are also evident. The islands are home to many species of algae, bryophytes, and lichens, twenty-seven species of vascular plants, many marine invertebrates, about one hundred terrestrial free-living invertebrates, twenty-nine seabird species, three seal species, and a resident population of killer whales. Globally significant populations of several pelagic seabird species breed on the islands, including the wandering albatross, Crozet shag, and Indian yellow-nosed albatross. The fish fauna are comparatively poorly known, although *Dissostichus eleginoides* (patagonian toothfish) was commercially exploited in the 1990s.

The vegetation can be split into two major biomes: polar desert and sub-Antarctic tundra. Polar desert occurs at elevations above 500 m. Here, there are no closed plant communities, and the cushion-plant *Azorella selago* is the only vascular plant species found in the biome, although it also disappears above c. 800 m. Polar desert is dominated by bryophytes and lichens, which are more common on less mobile substrates such as welded scoria or grey lava outcrops. The sub-Antarctic tundra biome can be divided into six major complexes, which are a consequence of differences in water availability and movement, and nutrient availability. These are the coastal salt-spray complex, fellfield complex, slope complex, biotic grassland complex, biotic herbfield complex, and mire complex. Invertebrate assemblages can be classified in a similar way, largely reflecting their response to the abiotic environment and the plant communities, although they also show much finer-scale spatial structuring.

The islands were discovered in 1663 by Barent Barentzoon Ham, and the first recorded landing was by a party of sealers in 1803/1804. Subsequently there was considerable sealing activity, and the islands were visited by several scientific expeditions, including *Challenger,* which was the first to put scientific personnel ashore. Owing to their strategic position, the islands were annexed for the colonial government of South Africa in 1947 by Lieutenant-Commander John Fairbairn of HMSAS *Transvaal*. Since then, South Africa has maintained a station at the islands. At first it was used solely for meteorological observations. The first biological and geological expedition took place in the 1965/1966 season, and both marine and terrestrial scientific research have been ongoing at the islands since that time. The dynamics of these systems and their interactions are now especially well studied and form the basis for ongoing investigations of system responses to environmental change.

Major conservation threats to the islands' biota and ecosystems include invasive alien species, global climate change, and exploitation of marine resources, which has both direct and indirect effects on pelagic seabirds and seals. The islands have been declared Special Nature Reserves under the South African National Environmental Management: Protected Areas Act, the highest level of protection any area can enjoy. They may be used for conservation and science only and are managed by the Prince Edward Islands Management Committee. Recently, the South African government announced its intention to declare the surrounding seas a Marine Protected Area.

Steven L. Chown

See also **Algae; *Challenger* Expedition (1872–1876); Climate Change; Killer Whale; Lichens; Polar Desert; Sealing, History of; Soils; South Africa; Volcanoes; Wandering Albatross; Yellow-Nosed Albatross**

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PRODUCTIVITY AND BIOMASS

Biomass is defined as the total weight (total numbers × average weight) of organisms in a given area or volume. *Productivity* is the amount of biomass produced in an area or volume over a period of time. It can be divided into *primary productivity,* which refers to the production of biomass by plants through photosynthesis, and *secondary productivity,* which is the rate of production of biomass by heterotrophs (organisms that consume other organisms).

Patterns of primary productivity dictate the structure of biological communities. Antarctica does not support many land-living plants and virtually all primary production takes place in the sea by small, single-celled algae called phytoplankton. Most are found either suspended close to the sea surface or attached to surface-dwelling ice so that they can obtain sufficient amounts of light. Phytoplankton have relatively short life cycles, lasting days to weeks, which results in a high rate of turnover. This can be described in terms of the ratio of annual production to biomass, (P:B y^{-1}), which is >10 y^{-1} for Southern Ocean phytoplankton compared with ~ 0.3 y^{-1} for terrestrial systems in other parts of the world, where biomass persists for years in trees.

Since the 1980s, satellites have mapped the colour of the surface of the ocean in order to determine the distribution of phytoplankton biomass. They found the Southern Ocean to be highly heterogeneous, with phytoplankton biomass tending to be low in open ocean regions and very high around island systems, oceanic fronts, and retreating ice edges. The availability of the trace element iron, which is required for photosynthesis, may be a cause of these differences.

Secondary productivity depends on primary productivity and there is frequently a positive relationship between the two. As a general rule, secondary productivity in herbivores is ten times less than the primary production on which it is based. This is because a lot of phytoplankton goes ungrazed, especially in Antarctica, where superblooms of diatoms and dinoflagellates saturate herbivore consumption. Further energy is lost through incomplete assimilation and respiration before consumed matter is converted to body mass. Planktonic heterotrophs have longer life cycles and slower turnover rates than phytoplankton: salps *(Salpa thompsoni)* live for about a year; krill *(Euphausia superba)* and copepods (e.g., *Calanoides acutus* and *Rhincalanus gigas*) live for 2 or more years. Correspondingly, their P:B ratios are lower (normally between 1 and 3 y^{-1}) than those of phytoplankton. The persistence of these animals over time means that their biomass levels can exceed those of phytoplankton, despite their smaller productivities. Around South Georgia, for instance, the combined biomass of krill and *C. acutus* (in grams carbon per m^2) is ~ 2.5, while that of phytoplankton is ~ 1.

The P:B ratios of benthic organisms (0.1 to 0.8 y^{-1}) are even smaller than those of zooplankton, reflecting the fact that most of these organisms have a long lifespan (>3 y) and generally grow slowly. Very few other benthic communities in the world reach the high levels of biomass observed on Antarctic shelf environments. In shallow waters the biomass (like biodiversity) is typically 10–1000 $g.m^2$ and can be very patchy. Sheltered areas may accumulate biomass >5000 $g.m^2$ whilst recently ice scoured areas can be ~ 1 $g.m^2$ or even less. Being large increases food-capturing area, which helps these creatures to make the most of the oscillating seasonal food supply as it falls from the productive layers above. The low ambient temperatures in this environment increase the availability of oxygen dissolved in water and reduce the maintenance costs that would otherwise prevent these animals from achieving such sizes.

Geraint A. Tarling

See also **Benthic Communities in the Southern Ocean; Pelagic Communities of the Southern Ocean; Phytoplankton; Polar Front**

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PROTECTED AREAS WITHIN THE ANTARCTIC TREATY AREA

The Antarctic Treaty Area is a protected area. The Antarctic Treaty itself contains measures to protect the region from damage by nuclear explosions and radioactive wastes, and in Article IX the intent was made clear that measures should be taken for the preservation and conservation of living resources. However, the treaty itself was not designed primarily for environmental protection, and soon after the treaty entered into force the parties introduced the Agreed Measures for the Conservation of Antarctic Fauna and Flora (1964), in which Antarctica was designated a "Special Conservation Area." From the outset, there was a recognition that despite the special conservation status accorded the region as a whole, there would be a need for more specific and stringent protection at particularly special or vulnerable sites. Thus, Article VIII of the Agreed Measures provided for designation of Specially Protected Areas (SPAs). The principal aim of SPAs was to preserve ecological systems that were unique or of outstanding scientific importance. All entry to SPAs was prohibited except in accordance with a permit, which could only be granted for a compelling scientific purpose that could not be served elsewhere.

There was also recognition of the need to afford protection to Historic Sites and Monuments (HSMs) at the first meeting of the treaty parties in 1961, and a formal list of sites was first adopted in 1972. In the same year, the Site of Special Scientific Interest (SSSI) category was introduced. In 1975, the category of Areas of Special Tourist Interest was agreed on, although none were ever designated. The category of Marine SSSI was introduced in 1987, while in 1989 two further categories, Specially Reserved Areas (SRAs) and Multiple-Use Planning Areas (MPAs) were agreed on. A special category, "Tomb," was assigned to the site of the 1979 aircraft crash on Mount Erebus, Ross Island, in order to ensure that it was left in peace. The purpose of these additional categories was to encompass a broader set of values for special protection than was possible under the provisions of the SPA. Although these categories did allow for inclusion of wider values, there remained lacking an overall strategic vision for development of the system.

At the time of agreement of the Protocol on Environmental Protection to the Antarctic Treaty in 1991, nineteen SPAs (fifteen of which were designated in 1966 soon after the category was introduced), thirty-five SSSIs (five of which were Marine), one Tomb, and fifty-nine HSMs had been designated. One SRA and one MPA were agreed on for voluntary observance, although these were never formally designated.

The Protocol on Environmental Protection to the Antarctic Treaty, in Article 2 (Objective and Designation), declares Antarctica "a natural reserve, devoted to peace and science," reaffirming the special conservation status accorded the area under the Agreed Measures. Moreover, the Protocol took steps to rationalize the rather unwieldy Antarctic protected area system that had evolved by replacing all of the previous categories, with the exception of HSMs, by two designations under Annex V on Area Protection and Management: Antarctic Specially Protected Areas (ASPAs) and Antarctic Specially Managed Areas (ASMAs). When Annex V came into force on 24 May 2002, all SPAs and SSSIs previously designated were incorporated as ASPAs, and renumbered by a three-digit schema (ASPA No. 101, ASPA No. 102, etc.) to avoid confusion with the old system. Functions previously covered by the other categories are included under the provisions for ASPAs and ASMAs. HSMs continue much as before, although they may also be designated as ASPAs or ASMAs if required.

Article 3 of Annex V stipulates that any area, including any marine area, may be designated as an Antarctic Specially Protected Area (ASPA) to protect outstanding environmental, scientific, historic, aesthetic, or wilderness values, any combination of those values, or ongoing or planned scientific research. Designation of a marine area requires the prior approval of the CCAMLR Commission. Areas designated should be of "sufficient size" to protect the identified values. The purpose of the ASMA is to improve the coordination of activities and to help minimise environmental impacts or risks of mutual interference within a specified area. Management plans are required for both ASPAs and ASMAs, and include an identification of site values, management objectives, a site description, and policies for the conduct of activities within the area. Entry into an ASPA is prohibited except by a permit issued according to the conditions prescribed by the management plan. Entry into an ASMA does not require a permit, but activities within are guided by the management plan and a Code of Conduct.

As of June 2006 there were sixty-seven ASPAs and four ASMAs formally designated, as well as seventy-six HSMs.

An important advance in Annex V is that it provides a stronger strategic vision for the development of the Antarctic protected areas network, and aims specifically to establish it on a more systematic basis by including the following:

1. Areas kept inviolate so that they may be available for future comparisons with localities that may have been affected by human activities.
2. Representative examples of major terrestrial and marine ecosystems.
3. Important or unusual assemblages of species.
4. Type localities or the only known habitats of particular species.

(Text continued on page 781)

Antarctic Specially Protected Areas (ASPAs) and Antarctic Specially Managed Areas (ASMAs) in the Antarctic Treaty Area as of June 2006

No.	Antarctic Specially Protected Areas	Former Site No.	Current Plan Adopted
101	Taylor Rookery, Mac.Robertson Land	SPA No. 1	1992
102	Rookery Islands, Holme Bay, Mac.Robertson Land	SPA No. 2	1992
103	Ardery Island and Odbert Island, Budd Coast	SPA No. 3	1992
104	Sabrina Island, Balleny Islands	SPA No. 4	N/A
105	Beaufort Island, Ross Sea	SPA No. 5	2003
	Cape Crozier, Ross Island—Redesignated SSSI No. 4 in 1975	SPA No. 6	2002
106	Cape Hallett, Victoria Land	SPA No. 7	2002
107	Emperor Island, Dion Islands, Marguerite Bay, Antarctic Peninsula	SPA No. 8	2002
108	Green Island, Berthelot Islands, Antarctic Peninsula	SPA No. 9	2002
	Byers Peninsula—Redesignated SSSI No. 6 in 1975	SPA No. 10	2002
	Cape Shirreff—Redesignated SSSI No. 32 in 1989	SPA No. 11	1989
	Fildes Peninsula—Redesignated SSSI No. 5 in 1975	SPA No. 12	1975
109	Moe Island, South Orkney Islands	SPA No. 13	1995
110	Lynch Island, South Orkney Islands	SPA No. 14	2000
111	Southern Powell Island and adjacent islands, South Orkney Islands	SPA No. 15	1995
112	Coppermine Peninsula, Robert Island, South Shetland Islands	SPA No. 16	1970
113	Litchfield Island, Arthur Harbour, Anvers Island, Palmer Archipelago	SPA No. 17	2004
114	Northern Coronation Island, South Orkney Islands	SPA No. 18	2003
115	Lagotellerie Island, Marguerite Bay, Antarctic Peninsula	SPA No. 19	2000
116	"New College Valley," Caughley Beach, Cape Bird, Ross Island	SPA No. 20	2000
117	Avian Island, off Adelaide Island, Antarctic Peninsula	SPA No. 21	2002
118	Summit of Mount Melbourne, Victoria Land (includes "Cryptogam Ridge")	SPA No. 22	2003
119	Forlidas Pond and Davis Valley ponds, Dufek Massif	SPA No. 23	1991
120	"Pointe-Géologie Archipelego," Terre Adélie	SPA No. 24	1995
121	Cape Royds, Ross Island	SSSI No. 1	2002
122	Arrival Heights, Hut Point Peninsula, Ross Island	SSSI No. 2	2004
123	Barwick and Balham Valleys, Victoria Land	SSSI No. 3	2002
124	Cape Crozier, Ross Island	SSSI No. 4	2002
125	Fildes Peninsula, King George Island, South Shetland Islands	SSSI No. 5	1975
126	Byers Peninsula, Livingston Island, South Shetland Islands	SSSI No. 6	2002
127	Haswell Island	SSSI No. 7	1975
128	Western shore of Admiralty Bay, King George Island	SSSI No. 8	2000
129	Rothera Point, Adelaide Island	SSSI No. 9	1996
	Caughley Beach—Incorporated into SPA No. 20 in 2000	SSSI No. 10	2000
130	"Tramway Ridge," Mount Erebus, Ross Island	SSSI No. 11	2002
131	Canada Glacier, Lake Fryxell, Taylor Valley, Victoria Land	SSSI No. 12	1997
132	Potter Peninsula, "25 de Mayo" (King George) Island, South Shetland Islands	SSSI No. 13	1997
133	Harmony Point, west coast of Nelson Island, South Shetland Islands	SSSI No. 14	1997
134	Cierva Point and offshore islands, Danco Coast, Antarctic Peninsula	SSSI No. 15	1997
135	Northeastern Bailey Peninsula, Budd Coast, Wilkes Land	SSSI No. 16	2003
136	Clark Peninsula, Budd Coast, Wilkes Land	SSSI No. 17	2000
137	Northwest White Island, McMurdo Sound	SSSI No. 18	2002
138	Linnaeus Terrace, Asgard Range, Victoria Land	SSSI No. 19	1996
139	Biscoe Point, Anvers Island	SSSI No. 20	2004
140	Parts of Deception Island, South Shetland Islands	SSSI No. 21	1985
141	"Yukidori Valley," Langhovde, Lützow-Holmbukta	SSSI No. 22	2000
142	Svarthamaren, Mühlig-Hofmannfjella, Dronning Maud Land	SSSI No. 23	2004
	Summit of Mount Melbourne—Incorporated into ASPA No. 118 in 2003	SSSI No. 24	2003
143	Marine Plain, Mule Peninsula, Vestfold Hills, Princess Elizabeth Land	SSSI No. 25	2003
144	"Chile Bay" (Discovery Bay), Greenwich Island, South Shetland Islands	SSSI No. 26	1987
145	Port Foster, Deception Island, South Shetland Islands	SSSI No. 27	1987
146	South Bay, Doumer Island, Palmer Archipelago	SSSI No. 28	1987
147	Ablation Valley–Ganymede Heights, Alexander Island	SSSI No. 29	2002
	Avian Island—Redesignated SPA No. 21 in 1991	SSSI No. 30	2002

(Continued)

Antarctic Specially Protected Areas (ASPAs) and Antarctic Specially Managed Areas (ASMAs) in the Antarctic Treaty Area as of June 2006 (Continued)

No.	Antarctic Specially Protected Areas	Former Site No.	Current Plan Adopted
148	Mount Flora, Hope Bay, Antarctic Peninsula	SSSI No. 31	2002
149	Cape Shirreff, Livingston Island, South Shetland Islands (also CEMP Site No. 2)	SSSI No. 32	1989
150	Ardley Island, Maxwell Bay, King George Island	SSSI No. 33	1991
151	Lions Rump, King George Island, South Shetland Islands	SSSI No. 34	2000
152	Western Bransfield Strait off Low Island, South Shetland Islands	SSSI No. 35	2003
153	Eastern Dallmann Bay off Brabant Island, Palmer Archipelago	SSSI No. 36	2003
154	Botany Bay, Cape Geology, Victoria Land	SSSI No. 37	2003
155	Cape Evans, Ross Island	SPA No. 25	1997
156	Lewis Bay, Mount Erebus, Ross Island	SPA No. 26	2003
157	Backdoor Bay, Cape Royds, Ross Island	SPA No. 27	2002
158	Hut Point, Ross Island	SPA No. 28	1998
159	Cape Adare, Borchgrevink Coast, Northern Victoria Land	SPA No. 29	1998
160	Frazier Islands, Wilkes Land, East Antarctica		2003
161	Terra Nova Bay, Victoria Land, Ross Sea		2003
162	Mawson's Huts, Commonwealth Bay, George V Land		2004
163	Dashkin Gangotri Glacier, Dronning Maud Land		2005
164	Scullin and Murray Monoliths, Mac.Robertson Land		2005
165	Edmonson Point, Wood Bay, Ross Sea		2006
166	Port-Martin, Terre Adélie		2006
167	Hawker Island, Vestfold Hills, Ingrid Christensen Coast, Princess Elizabeth Land, East Antarctica		2006

No.	Antarctic Specially Managed Areas		
1	Admiralty Bay, King George Island, South Shetland Islands		1996
2	McMurdo Dry Valleys, Southern Victoria Land		2004
3	Cape Denison, Commonwealth Bay, George V Land		2004
4	Deception Island, South Shetland Islands		2005

Historic Sites and Monuments (HSMs) in the Antarctic Treaty Area as of June 2006

No.	Description	Proposer	Latitude	Longitude
1	Flag mast erected in December 1965 at the South Geographical Pole by the First Argentine Overland Polar Expedition.	Argentina	90° S	
2	Rock cairn and plaques at Syowa Station in memory of Shin Fukushima, a member of the 4th Japanese Antarctic Research Expedition, who died in October 1960 while performing official duties. The cairn was erected on 11 January 1961, by his colleagues. Some of his ashes repose in the cairn.	Japan	69°00′ S	39°35′ E
3	Rock cairn and plaque on Proclamation Island, Enderby Land, erected in January 1930 by Sir Douglas Mawson. The cairn and plaque commemorate the landing on Proclamation Island of Sir Douglas Mawson with a party from the British, Australian, and New Zealand Antarctic Research Expedition of 1929–1931.	Australia	65°51′ S	53°41′ E
4	Station building to which a bust of V. I. Lenin is fixed, together with a plaque in memory of the conquest of the Pole of Inaccessibility by Soviet Antarctic explorers in 1958.	Russia	83°06′ S	54°58′ E

(Continued)

Historic Sites and Monuments (HSMs) in the Antarctic Treaty Area as of June 2006 (Continued)

No.	Description	Proposer	Latitude	Longitude
5	Rock cairn and plaque at Cape Bruce, Mac.Robertson Land, erected in February 1931 by Sir Douglas Mawson. The cairn and plaque commemorate the landing on Cape Bruce of Sir Douglas Mawson with a party from the British, Australian, and New Zealand Antarctic Research Expedition of 1929–1931.	Australia	67°25′ S	60°47′ E
6	Rock cairn at Walkabout Rocks, Vestfold Hills, Princess Elizabeth Land, erected in 1939 by Sir Hubert Wilkins. The cairn houses a canister containing a record of his visit.	Australia	68°22′ S	78°33′ E
7	Stone with inscribed plaque, erected at Mirny Observatory, Mabus Point, in memory of driver–mechanic Ivan Kharma, who perished on fast ice in the performance of official duties in 1956.	Russia	66°33′ S	93°01′ E
8	Metal monument-sledge at Mirny Observatory, Mabus Point, with plaque in memory of driver–mechanic Anatoly Shcheglov, who perished in the performance of official duties.	Russia	66°33′ S	93°01′ E
9	Cemetery on Buromskiy Island, near Mirny Observatory, in which are buried Soviet, Czechoslovakian, and GDR citizens, members of Soviet Antarctic Expeditions, who perished in the performance of official duties on 3 August 1960.	Russia	66°32′ S	93°01′ E
10	Building (magnetic observatory) at Dobrowolsky Station, Bunger Hills, with plaque in memory of the opening of Oasis Station in 1956.	Russia	66°16′ S	100°45 ′E
11	Heavy tractor at Vostok Station with plaque in memory of the opening of the Station in 1957.	Russia	78°28′ S	106°48′ E
12	Delisted.			
13	Delisted.			
14	Site of ice cave at Inexpressible Island, Terra Nova Bay, constructed in March 1912 by Victor Campbell's Northern Party, British Antarctic Expedition, 1910–1913. The party spent the winter of 1912 in this ice cave. A wooden sign, plaque, and seal bones remain at the site.	New Zealand	74°54′ S	163°43′ E
15	Hut at Cape Royds, Ross Island, built in February 1908 by the British Antarctic Expedition of 1907–1909, led by Sir Ernest Shackleton. Restored in January 1961 by the Antarctic Division of New Zealand Department of Scientific and Industrial Research. Site incorporated within ASPA 157.	New Zealand/ UK	77°33′ S	166°10′ E
16	Hut at Cape Evans, Ross Island, built in January 1911 by the British Antarctic Expedition of 1910–1913, led by Captain Robert F. Scott. Restored in January 1961 by the Antarctic Division of New Zealand Department of Scientific and Industrial Research. Site incorporated within ASPA 155.	New Zealand/ UK	77°38′ S	166°24′ E
17	Cross on Wind Vane Hill, Cape Evans, Ross Island, erected by the Ross Sea Party, led by Captain Aeneas Mackintosh, of Sir Ernest Shackleton's Imperial Trans-Antarctic Expedition of 1914–1916, in memory of three members of the party who died in the vicinity in 1916. Site incorporated within ASPA 155.	New Zealand/ UK	77°38′ S	166°24′ E

(Continued)

Historic Sites and Monuments (HSMs) in the Antarctic Treaty Area as of June 2006 (Continued)

No.	Description	Proposer	Latitude	Longitude
18	Hut at Hut Point, Ross Island, built in February 1902 by the British Antarctic Expedition of 1901–1904, led by Captain Robert F. Scott. Partially restored in January 1964 by the New Zealand Antarctic Society, with assistance from the United States Government. Site incorporated within ASPA 158.	New Zealand/ UK	77°50′ S	166°37′ E
19	Cross at Hut Point, Ross Island, erected in February 1904 by the British Antarctic Expedition of 1901–1904, in memory of George Vince, a member of the expedition, who died in the vicinity.	New Zealand/ UK	77°50′ S	166°37′ E
20	Cross on Observation Hill, Ross Island, erected in January 1913 by the British Antarctic Expedition of 1910–1913, in memory of Captain Robert F. Scott's party, which perished on the return journey from the South Pole in March 1912.	New Zealand/ UK	77°51′ S	166°41′ E
21	Remains of stone hut at Cape Crozier, Ross Island, constructed in July 1911 by Edward Wilson's party of the British Antarctic Expedition (1910–1913) during the winter journey to collect Emperor penguin eggs.	New Zealand	77°31′ S	169°22′ E
22	Three huts and associated historic relics at Cape Adare. Two were built in February 1899 during the British Antarctic *(Southern Cross)* Expedition, 1898–1900, led by Carsten E. Borchgrevink. The third was built in February 1911 by Robert F. Scott's Northern Party, led by Victor L. A.Campbell. Scott's Northern Party hut has largely collapsed, with only the porch standing in 2002. Site incorporated within ASPA 159.	New Zealand/ UK	71°18′ S	170°12′ E
23	Grave at Cape Adare of Norwegian biologist Nicolai Hanson, a member of the British Antarctic *(Southern Cross)* Expedition, 1898–1900, led by Carsten E. Borchgrevink. A large boulder marks the head of the grave with the grave itself outlined in white quartz stones. A cross and plaque are attached to the boulder.	New Zealand/ UK	71°17′ S	170°13′ E
24	Rock cairn, known as "Amundsen's cairn," on Mount Betty, Queen Maud Range, erected by Roald Amundsen on 6 January 1912, on his way back to *Framheim* from the South Pole.	Norway	85°11′ S	163°45′ W
25	Delisted.			
26	Abandoned installations of Argentine Station "General San Martin" on Barry Island, Debenham Islands, Marguerite Bay, with cross, flag mast, and monolith built in 1951.	Argentina	68°08′ S	67°08′ W
27	Cairn with a replica of a lead plaque erected on Megalestris Hill, Petermann Island, in 1909 by the second French expedition led by Jean-Baptiste E. A. Charcot. The original plaque is in the reserves of the Museum National d'Histoire Naturelle (Paris).	Argentina/ France/UK	65°10′ S	64°09′ W
28	Rock cairn at Port Charcot, Booth Island, with wooden pillar and plaque inscribed with the names of the first French expedition led by Jean-Baptiste E. A. Charcot, which wintered here in 1904 aboard *Le Français*.	Argentina	65°03′ S	64°01′ W
29	Lighthouse named "Primero de Mayo" erected on Lambda Island, Melchior Islands, by Argentina in 1942. This was the first Argentine lighthouse in the Antarctic.	Argentina	64°18′ S	62°59′ W

(Continued)

Historic Sites and Monuments (HSMs) in the Antarctic Treaty Area as of June 2006 (Continued)

No.	Description	Proposer	Latitude	Longitude
30	Shelter at Paradise Harbour erected in 1950 near the Chilean Base "Gabriel Gonzalez Videla" to honour Gabriel Gonzalez Videla, the first head of state to visit the Antarctic. The shelter is a representative example of pre-IGY activity and constitutes an important national commemoration.	Chile	64°49′ S	62°51′ W
31	Delisted.			
32	Concrete monolith erected in 1947, near Capitán Arturo Prat Base on Greenwich Island, South Shetland Islands. Point of reference for Chilean Antarctic hydrographic surveys. The monolith is representative of an important pre-IGY activity and is currently preserved and maintained by personnel from Prat Base.	Chile	62°28′ S	59°40′ W
33	Shelter and cross with plaque near Capitán Arturo Prat Base (Chile), Greenwich Island, South Shetland Islands. Named in memory of Lieutenant-Commander González Pacheco, who died in 1960 while in charge of the station. The monument commemorates events related to a person whose role and the circumstances of whose death have a symbolic value and the potential to educate people about significant human activities in Antarctica.	Chile	62°29′ S	59°40′ W
34	Bust at Capitán Arturo Prat Base (Chile), Greenwich Island, South Shetland Islands, of the Chilean naval hero Arturo Prat, erected in 1947. The monument is representative of pre-IGY activities and has symbolic value in the context of the Chilean presence in Antarctica.	Chile	62°50′ S	59°41′ W
35	Wooden cross and statue of the Virgin of Carmen erected in 1947 near Capitán Arturo Prat Base (Chile), Greenwich Island, South Shetland Islands. The monument is representative of pre-IGY activities and has a particularly symbolic and architectural value.	Chile	62°29′ S	59°40′ W
36	Replica of a metal plaque erected by Eduard Dallmann at Potter Cove, King George Island, to commemorate the visit of his German expedition on 1 March, 1874 on board *Grönland*.	Argentina/ UK	62°14′ S	58°39′ W
37	Statue erected in 1948 at General Bernardo O'Higgins Base (Chile), Trinity Peninsula, of Bernardo O'Higgins, the first ruler of Chile to envisage the importance of Antarctica. This monument is representative of pre-IGY activities in Antarctica and has a symbolic meaning in the history of Antarctic exploration since it was during O'Higgins's government that the vessel *Dragon* landed on the coast of the Antarctic Peninsula in 1820.	Chile	63°19′ S	57°54′ W
38	Wooden hut on Snow Hill Island built in February 1902 by the main party of the Swedish South Polar Expedition led by Otto Nordenskjöld.	Argentina/ UK	64°22′ S	56°59′ W
39	Stone hut at Hope Bay, Trinity Peninsula, built in January 1903 by a party of the Swedish South Polar Expedition.	Argentina/ UK	63°24′ S	56°59′ W
40	Bust of General San Martin, grotto with a statue of the Virgin of Lujan, and a flag mast at Base "Esperanza," Hope Bay, erected by Argentina in 1955, together with a graveyard with stele in memory of members of Argentine expeditions who died in the area.	Argentina	63°24′ S	56°59′ W

(Continued)

Historic Sites and Monuments (HSMs) in the Antarctic Treaty Area as of June 2006 (Continued)

No.	Description	Proposer	Latitude	Longitude
41	Stone hut on Paulet Island built in February 1903 by survivors of the wrecked vessel *Antarctic* under Captain Carl A. Larsen, members of the Swedish South Polar Expedition led by Otto Nordenskjöld, together with a grave of a member of the expedition and the rock cairn built by the survivors of the wreck at the highest point of the island to draw the attention of rescue expeditions.	Argentina/ UK	63°34′ S	55°45′ W
42	Area of Scotia Bay, Laurie Island, South Orkney Island, in which are found a stone hut built in 1903 by the Scottish Antarctic Expedition led by William S. Bruce; the Argentine meteorological hut and magnetic observatory, built in 1905 and known as Moneta House; and a graveyard with twelve graves, the earliest of which dates from 1903.	Argentina	60°46′ S	44°40′ W
43	Cross erected in 1955, at a distance of 1300 m northeast of the Argentine General Belgrano I Station (Argentina), subsequently moved to Belgrano II Station (Argentina), Nunatak Bertrab, Confin Coast, Coats Land in 1979.	Argentina	77°52′ S	34°37′ W
44	Plaque erected at the temporary Indian station "Dakshin Gangotri," Princess Astrid Kyst, Dronning Maud Land, listing the names of the First Indian Antarctic Expedition, which landed nearby on 9 January 1982.	India	70°45′ S	11°38′ E
45	Plaque on Brabant Island, on Metchnikoff Point, mounted at a height of 70 m on the crest of the moraine separating this point from the glacier and bearing the following inscription: This monument was built by François de Gerlache and other members of the Joint Services Expedition 1983–1985 to commemorate the first landing on Brabant Island by the Belgian Antarctic Expedition, 1897–1899: Adrien de Gerlache de Gomery (Belgium), leader, Roald Amundsen (Norway), Henryk Arctowski (Poland), Frederick Cook (USA), and Emile Danco (Belgium) camped nearby from 30 January to 6 February 1898.	Belgium	64°02′ S	62°34′ W
46	All the buildings and installations of Port-Martin base, Terre Adélie constructed in 1950 by the 3rd French expedition in Terre Adélie and partly destroyed by fire during the night of 23 to 24 January 1952.	France	66°49′ S	141°24′ E
47	Wooden building called "Base Marret" on the Île des Pétrels, Terre Adélie, where seven men under the command of Mario Marret overwintered in 1952 following the fire at Port Martin Base.	France	66°40′ S	140°01′ E
48	Iron cross on the North-East headland of the Île des Pétrels, Terre Adélie, dedicated as a memorial to André Prudhomme, head meteorologist in the 3rd International Geophysical Year expedition, who disappeared during a blizzard on 7 January 1959.	France	66°40′ S	140°01′ E
49	The concrete pillar erected by the First Polish Antarctic Expedition at Dobrolowski Station on the Bunger Hill to measure acceleration due to gravity $g = 982{,}439.4$ mgal $\pm$ 0.4 mgal in relation to Warsaw, according to the Potsdam system, in January 1959.	Poland	66°16′ S	100°45′ E

(Continued)

Historic Sites and Monuments (HSMs) in the Antarctic Treaty Area as of June 2006 (Continued)

No.	Description	Proposer	Latitude	Longitude
50	A brass plaque bearing the Polish Eagle, the national emblem of Poland, the dates 1975 and 1976, and the following text in Polish, English, and Russian: "In memory of the landing of members of the first Polish Antarctic marine research expedition on the vessels 'Profesor Siedlecki' and 'Tazar' in February 1976." This plaque, southwest of the Chilean and Soviet stations, is mounted on a cliff facing Maxwell Bay, Fildes Peninsula, King George Island.	Poland	62°12′ S	59°01′ W
51	The grave of Wlodzimierz Puchalski, surmounted by an iron cross, on a hill to the south of Arctowski station on King George Island. W. Puchalski was an artist and a producer of documentary nature films, who died on 19 January 1979 whilst working at the station.	Poland	62°13′ S	58°28′ W
52	Monolith erected to commemorate the establishment on 20 February 1985 by the People's Republic of China of the "Great Wall Station" on Fildes Peninsula, King George Island, in the South Shetland Islands. Engraved on the monolith is the following inscription in Chinese: "Great Wall Station, First Chinese Antarctic Research Expedition, 20 February 1985."	China	62°13′ S	58°58′ W
53	Bust of Captain Luis Alberto Pardo, monolith and plaques on Point Wild, Elephant Island, South Shetland Islands, celebrating the rescue of the survivors of the British ship *Endurance* by the Chilean Navy cutter *Yelcho,* displaying the following words: "Here on August 30th, 1916, the Chilean Navy cutter *Yelcho* commanded by Pilot Luis Pardo Villalón rescued the 22 men from the Shackleton Expedition who survived the wreck of the 'Endurance' living for four and one half months in this Island." The monolith and the plaques have been placed on Elephant Island and their replicas on the Chilean bases Capitan Arturo Prat (62°30′ S, 59°49′ W) and President Eduardo Frei (62°12′ S, 62°12′ W). Bronze busts of the pilot Luis Pardo Villalon were placed on the three aforementioned monoliths during the XXIVth Chilean Antarctic Scientific Expedition in 1987–1988.	Chile	61°03′ S	54°50′ W
54	Richard E. Byrd Historic Monument, McMurdo Station, Antarctica. Bronze bust on black marble, 5 ft high by 2 ft square, on wood platform, bearing inscriptions describing the polar achievements of Richard Evelyn Byrd. Erected at McMurdo Station in 1965.	USA	77°51′ S	166°40 ′E
55	East Base, Antarctica, Stonington Island. Buildings and artefacts at East Base, Stonington Island, and their immediate environs. These structures were erected and used during two US wintering expeditions: the Antarctic Service Expedition (1939–1941) and the Ronne Antarctic Research Expedition (1947–1948). The size of the historic area is approximately 1000 m in the north–south direction (from the beach to Northeast Glacier adjacent to Back Bay) and approximately 500 m in the east–west direction.	USA	68°11′ S	67°00′ W

(Continued)

Historic Sites and Monuments (HSMs) in the Antarctic Treaty Area as of June 2006 (Continued)

No.	Description	Proposer	Latitude	Longitude
56	Waterboat Point, Danco Coast, Antarctic Peninsula. The remains and immediate environs of the Waterboat Point hut. It was occupied by the UK two-man expedition of Thomas W. Bagshawe and Maxime C. Lester in 1921–1922. Only the base of the boat, foundations of doorposts and an outline of the hut and extension still exist. It is situated close to the Chilean station "President Gabriel Gonzáles Videla."	Chile/UK	64°49′ S	62°51′ W
57	Commemorative plaque at "Yankee Bay" (Yankee Harbour), MacFarlane Strait, Greenwich Island, South Shetland Islands. Near a Chilean refuge. Erected to the memory of Captain Andrew MacFarlane, who in 1820 explored the Antarctic Peninsula area in the brigantine *Dragon*.	Chile/UK	62°32′ S	59°45′ W
58	Delisted.			
59	A cairn on Half Moon Beach, Cape Shirreff, Livingston Island, South Shetland Islands, and a plaque on "Cerro Gaviota" opposite San Telmo Islets commemorating the officers, soldiers, and seamen aboard the Spanish vessel *San Telmo,* which sank in September 1819; possibly the first people to live and die in Antarctica. Site incorporated within ASPA 149.	Chile/Spain/ Peru	62°28′ S	60°46′ W
60	Wooden plaque and cairn located at Penguins Bay, southern coast of Seymour Island (Marambio), James Ross Archipelago. This plaque was placed on 10 November 1903 by the crew of a rescue mission of the Argentinian Corvette *Uruguay* in the site where they met the members of the Swedish expedition led by Dr. Otto Nordenskjöld. The text of the wooden plaque reads as follows: "10.XI.1903 Uruguay (Argentine Navy) in its journey to give assistance to the Swedish Antarctic expedition." In January 1990, a rock cairn was erected by Argentina in memory of this event in the place where the plaque is located.	Argentina	64°16′ S	56°39′ W
61	"Base A" at Port Lockroy, Goudier Island, off Wiencke Island, Antarctic Peninsula. Of historic importance as an Operation Tabarin base from 1944 and for scientific research, including the first measurements of the ionosphere, and the first recording of an atmospheric whistler, from Antarctica. Port Lockroy was a key monitoring site during the International Geophysical Year of 1957/1958.	UK	64°49′ S	63°29′ W
62	"Base F (Wordie House)" on Winter Island, Argentine Islands. Of historic importance as an example of an early British scientific base.	UK	65°15′ S	64°16′ W
63	"Base Y" on Horseshoe Island, Marguerite Bay, western Graham Land. Noteworthy as a relatively unaltered and completely equipped British scientific base of the late 1950s. "Blaiklock," the refuge hut nearby, is considered an integral part of the base.	UK	67°48′ S	67°18′ W
64	"Base E" on Stonington Island, Marguerite Bay, western Graham Land. Of historical importance in the early period of exploration and later British Antarctic Survey (BAS) history of the 1960s and 1970s.	UK	68°11′ S	67°00′ W

(Continued)

Historic Sites and Monuments (HSMs) in the Antarctic Treaty Area as of June 2006 (Continued)

No.	Description	Proposer	Latitude	Longitude
65	Message post, Svend Foyn Island, Possession Islands. A pole with a box attached was placed on the island on 16 January 1895 during the whaling expedition of Henryk Bull and Captain Leonard Kristensen of the ship *Antarctic*. It was examined and found intact by the British Antarctic Expedition of 1898–1900 and then sighted from the beach by the USS *Edisto* in 1956 and USCGS *Glacier* in 1965.	New Zealand/ Norway/UK	71°56′ S	171°05′ W
66	Prestrud's Cairn, Scott Nunataks, Alexandra Mountains, Edward VII Peninsula. The small rock cairn was erected at the foot of the main bluff on the north side of the nunataks by Lieutenant K. Prestrud on 3 December 1911 during the Norwegian Antarctic Expedition of 1910–1912.	New Zealand/ Norway/UK	77°11′ S	154°32′ W
67	Rock shelter, "Granite House," Cape Geology, Granite Harbour. This shelter was constructed in 1911 for use as a field kitchen by Griffith Taylor's second geological excursion during the British Antarctic Expedition of 1910–1913. It was enclosed on three sides with granite boulder walls and used a sledge to support a seal-skin roof. The stone walls of the shelter have partially collapsed. The shelter contains corroded remnants of tins, a seal skin, and some cord. The sledge is now located 50 m seaward of the shelter and consists of a few scattered pieces of wood, straps, and buckles. Site incorporated within ASPA 154.	New Zealand/ Norway/UK	77°00′ S	162°32′ E
68	Site of depot at Hells Gate Moraine, Inexpressible Island, Terra Nova Bay. This emergency depot consisted of a sledge loaded with supplies and equipment that was placed on 25 January 1913 by the British Antarctic Expedition, 1910–1913. The sledge and supplies were removed in 1994 in order to stabilize their deteriorating condition.	New Zealand/ Norway/UK	74°52′ S	163°50′ E
69	Message post at Cape Crozier, Ross Island, erected on 22 January 1902 by Captain Robert F. Scott's *Discovery* Expedition of 1901–1904. It was to provide information for the expedition's relief ships, and held a metal message cylinder, which has since been removed. Site incorporated within ASPA 124.	New Zealand/ Norway/UK	77°27′ S	169°16′ E
70	Message post at Cape Wadworth, Coulman Island. A metal cylinder nailed to a red pole 8 m above sea level, placed by Captain Robert F. Scott on 15 January 1902. He painted the rocks behind the post red and white to make it more conspicuous.	New Zealand/ Norway/UK	73°19′ S	169°47′ E
71	Whalers Bay, Deception Island, South Shetland Islands. The site comprises all pre-1970 remains on the shore of Whalers Bay, including those from the early whaling period (1906–1912) initiated by Captain Adolfus Andresen of the Sociedad Ballenera de Magallanes, Chile; the remains of the Norwegian Hektor Whaling Station established in 1912 and all artefacts associated with its operation until 1931; the site of a cemetery with 35 burials and a memorial to 10 men lost at sea; and the remains from the period of British scientific and	Chile/Norway	62°59′ S	60°34′ W

(Continued)

Historic Sites and Monuments (HSMs) in the Antarctic Treaty Area as of June 2006 (Continued)

No.	Description	Proposer	Latitude	Longitude
	mapping activity (1944–1969). The site also acknowledges and commemorates the historic value of other events that occurred there, from which nothing remains.			
72	Mikkelsen Cairn, Tryne Islands, Vestfold Hills. A rock cairn and a wooden mast erected by the landing party led by Captain Klarius Mikkelsen of the Norwegian whaling ship *Thorshavn* and including Caroline Mikkelsen, Captain Mikkelsen's wife, the first woman to set foot on East Antarctica. The cairn was discovered by Australian National Antarctic Research Expedition field parties in 1957 and again in 1995.	Australia/ Norway	68°22′ S	78°24′ E
73	Memorial Cross for the 1979 Mount Erebus crash victims, Lewis Bay, Ross Island. A cross of stainless steel that was erected in January 1987 on a rocky promontory 3 km from the Mount Erebus crash site in memory of the 257 people of different nationalities who lost their lives when the aircraft in which they were travelling crashed into the lower slopes of Mount Erebus, Ross Island. The cross was erected as a mark of respect and in remembrance of those who died in the tragedy.	New Zealand	77°25′ S	167°27′ E
74	The unnamed cove on the southwest coast of Elephant Island, including the foreshore and the intertidal area, in which the wreckage of a large wooden sailing vessel is located.	UK	61°14′ S	55°22′ W°
75	The A Hut of Scott Base, being the only existing Trans-Antarctic Expedition 1956/1957 building in Antarctica, sited at Pram Point, Ross Island, Ross Sea Region, Antarctica.	New Zealand	77°51′ S	166°46′ E
76	The ruins of the Base Pedro Aguirre Cerda Station, a Chilean meteorological and volcanological center situated at Pendulum Cove, Deception Island, Antarctica, that was destroyed by volcanic eruptions in 1967 and 1969.	Chile	62°59′ S	60°40′ W
77	Cape Denison, Commonwealth Bay, George V Land, including Boat Harbour and the historic artefacts contained within its waters. Site incorporated within ASMA No. 3. Part of this site also designated as ASPA No. 162.	Australia	67°00′30″ S	142°39′40″ E
78	Memorial plaque at India Point, Humboldt Mountains, Wohlthat Massif, central Dronning Maud Land, erected in memory of three scientists of the Geological Survey of India (GSI) and a communication technician from the Indian Navy—all members of the ninth Indian Expedition to Antarctica, who sacrificed their lives in this mountain camp in an accident on 8 January 1990.	India	71°45′08″ S	11°12′30″ E
79	Lillie Marleen Hut, Mount Dockery, Everett Range, Northern Victoria Land, erected to support the work of the German Antarctic Northern Victoria Land Expedition (GANOVEX I) of 1979/1980. The hut, a bivouac container made of prefabricated fibreglass units insulated with polyurethane foam, was named after the Lillie Glacier and the song "Lillie Marleen." The hut is closely associated with the dramatic sinking of the expedition ship *Gotland II* during GANOVEX II in December 1981.	Germany	71°12′S	164°31′E

(Continued)

Historic Sites and Monuments (HSMs) in the Antarctic Treaty Area as of June 2006 (Continued)

No.	Description	Proposer	Latitude	Longitude
80	Amundsen's Tent, erected at 90º by the Norwegian group of explorers led by Roald Amundsen on their arrival at the South Pole on 14 December 1911. The tent is currently buried underneath the snow and ice in the vicinity of the South Pole.	Norway	In the vicinity of 90° S	
81	Rocher du Débarquement (Landing Rock), Terre Adélie. A small island where Dumont D'Urville and his crew landed on 21 January 1840 when he discovered Terre Adélie.	France	66°36′18″ S	140°03′51″ E

5. Areas of particular scientific interest.
6. Examples of outstanding geological, glaciological, or geomorphological features.
7. Areas of outstanding aesthetic and wilderness value.
8. Sites or monuments of recognized historic value.
9. Any other areas that may be appropriate to protect the values set out in Article 3.

This framework allows for the development of a comprehensive system of specially protected areas in Antarctica. However, progress towards that comprehensive, representative system has so far been limited, and current sites are largely those that were designated prior to agreement on the Protocol. For example, most ASPAs are on land concentrated around the coast, are within close proximity of stations, and are found particularly along the Antarctic Peninsula and in the McMurdo Sound region of the Ross Sea. There are few marine ASPAs, and these are of limited size. Biological and scientific values are best represented, whilst relatively few sites have been designated for other purposes. Most sites aim to protect a few specific values or features, rather than represent an ecosystem. None has been designated specifically for aesthetic and wilderness values. In part, the slowness to introduce new areas since agreement on the Protocol has been caused by the practical need to engage much effort in preparing new or revised management plans for the existing protected areas to meet the more demanding requirements of Annex V.

To a large extent, the distribution of ASPAs mirrors the concentration on human activities in Antarctica, and thus also the pressures on the environment that exist or have been perceived. The distribution of activities has also strongly influenced the availability of knowledge from which to discriminate areas with values that may be worthy of designation. Without such knowledge, the scientific basis for selection and design of specific areas to include in the system is constrained. This is particularly the case in the Antarctic marine environment, where data are often relatively sparse. However, it would be unwise to wait until all gaps in knowledge have been filled before taking steps to expand the range of environment types represented in the system. Human activity, and possibly impacts, may expand into these areas more rapidly than detailed databases and knowledge can be acquired. An initial response to this dilemma may be to undertake a systematic and detailed appraisal of the gaps and needs for special protection in Antarctica, with a view to identifying values and areas that deserve priority attention. Focussed effort might then be made to develop the protected area network in Antarctica on a more systematic basis, working towards the more comprehensive and representative system envisaged in the Protocol.

Other protected areas designated under Conventions within the Antarctic Treaty system are the CCAMLR Ecosystem Monitoring Programme (CEMP), sites under the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR), and Seal Reserves under the Convention for the Conservation of Antarctic Seals (CCAS).

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See also **Antarctic: Definitions and Boundaries; Antarctic Peninsula; Antarctic Treaty System; Conservation; Conservation of Antarctic Fauna and Flora: Agreed Measures; Convention on the Conservation of Antarctic Seals; Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Mount Erebus; Protocol on Environmental Protection to the Antarctic Treaty; Ross Island**

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PROTOCOL ON ENVIRONMENTAL PROTECTION TO THE ANTARCTIC TREATY

The Development of a Comprehensive Environmental Protocol

Between 1981 and 1988, the Antarctic Treaty Consultative Parties were working on developing a mineral resource convention (Convention on the Regulation of Antarctic Resource Activities, or CRAMRA), a regime that would have provided an environmentally based regulatory framework for future mineral resource development. CRAMRA never entered into force, as Australia and France in 1989, later followed by other nations, decided against ratification. These parties advocated instead that comprehensive environmental protection measures be put in place for Antarctic activities.

Many of the mechanisms of environmental protection that had been included in CRAMRA had actually drawn upon earlier adopted hortatory recommendations, and it was consequently recognized that it would be helpful to collect, codify, and, to the degree necessary, extend the existing system of environmental measures in Antarctica into a harmonized and comprehensive framework.

Thus, acknowledging this need, the consultative parties decided to undertake as a priority objective to further elaborate a comprehensive system for the protection of the Antarctic environment. To contribute to this objective, a Special Antarctic Treaty Consultative Meeting was called for in 1990 to explore and discuss all aspects of such a proposal (Recommendation XV-1 [1989]).

The first session of the eleventh Antarctic Treaty Special Consultative Meeting was held at Viña del Mar (Chile) from November 19 to December 6, 1990. Mr. Oscar Pinochet de la Barra, Head of the Delegation of Chile, acted as Chairman for this session.The second session took place in Madrid (Spain) from April 22 to 30, from June 17 to 22, and from October 3 to 4, 1990 under the chairmanship of Mr. Carlos Blasco Villa, Head of the Delegation of Spain.

At the first session, debate on the form and content of the environmental framework to be developed was discussed, and a number of proposals were put forward. Australia, Belgium, France, and Italy advocated for a separate convention; some countries promoted a framework protocol, supported by drafts submitted by the UK and US; while New Zealand fronted a comprehensive protocol.

After extensive debates and discussions, as well as informal consultations, a compromise text was submitted by the Norwegian diplomat Rolf Trolle Andersen. The work at the following session in Madrid was greatly facilitiated by the Andersen text. Further deliberations followed, including extensive legal drafting work led by Mr. Pieter Verbeek from The Netherlands.

On October 4, 1991, the Representatives of the Consultative Parties adpoted by consensus the Protocol on Environmental Protection to the Antarctic Treaty, of which four Annexes form an integral part, concerning environmental impact assessment (Annex I), conservation of Antarctic fauna and flora (Annex II), waste disposal and management (Annex III), and prevention of marine pollution (Annex IV).

Parties to the Protocol on Environmental Protection to the Antarctic Treaty

Country	Date of Signature	Date of Ratification
Argentina	4 Oct. 1991	28 Oct. 1993
Australia	4 Oct. 1991	6 April 1994
Belgium	4 Oct. 1991	26 April 1996
Brazil	4 Oct. 1991	15 Aug. 1995
Bulgaria		21 April 1998[1]
Canada	4 Oct. 1991	13 Nov. 2003
Czech Republic	1 Jan. 1993	25 Aug. 2004
Chile	4 Oct. 1991	11 Jan. 1995
China	4 Oct. 1991	2 Aug. 1994
Ecuador	4 Oct. 1991	4 Jan. 1993
Finland	4 Oct. 1991	1 Nov. 1996
France	4 Oct. 1991	5 Feb. 1993
Germany	4 Oct. 1991	25 Nov. 1994
Greece	4 Oct. 1991	23 May 1995
India	2 July 1992	26 April 1996
Italy	4 Oct. 1991	31 March 1995
Japan	29 Sept. 1992	15 Dec. 1997
Korea, Republic of	2 July 1992	2 Jan. 1996
Netherlands	4 Oct. 1991	14 April 1994
New Zealand	4 Oct. 1991	22 Dec. 1994
Norway	4 Oct. 1991	16 June 1993
Peru	4 Oct. 1991	8 March 1993
Poland	4 Oct. 1991	1 Nov. 1995
Russian Federation	4 Oct. 1991	6 Aug. 1997
South Africa	4 Oct. 1991	3 Aug. 1995
Spain	4 Oct. 1991	1 July 1992
Sweden	4 Oct. 1991	30 March 1994
Ukraine		25 May 2001[1]
United Kingdom	4 Oct. 1991	25 April 1995
United States of America	4 Oct. 1991	17 April 1997
Uruguay	4 Oct. 1991	11 Jan. 1995

[1]Date deposit of accession. Entry into force 30 days after the deposit of accession.

Thus, within only 2 years of the collapse of CRAMRA, the Protocol on Environmental Protection to the Antarctic Treaty was signed. In the protocol, the Parties commit themselves to the comprehensive protection of the Antarctic environment and dependent and associated ecosystems.

The protocol in short does the following:

- Designates Antarctica a "natural reserve, devoted to peace and science."
- Establishes environmental principles for the conduct of all activities.
- Establishes an indefinite moratorium on mining (which in principle can be renegotiated 50 years after the coming into force of the protocol).
- Subjects all activities to prior assessment of environmental impacts.
- Provides for the establishment of a Committee for Environmental Protection, to advise the Antarctic Treaty Consultative Parties.

The Coming into Force of the Protocol

Article 23 (1) of the protocol established that the protocol should enter into force on the 30th day following the ratification by all states that were Antarctic Treaty Consultative Partes at the date on which the protocol was adopted.

At the conclusion of the negotiations of the Protocol on Environmental Protection it was recorded that it was desirable to ensure the effective implementation at an early date of the provisions of the protocol. Therefore, pending the entry into force of the protocol, it was agreed that all parties should aim to the extent practicable to apply the protocol provisions, as well as Annexes I–IV, in accordance with their legal systems.

In the aftermath of the adoption of the protocol, and before it came into force, the parties elaborated and adopted national implementing legislation for the protocol, and many parties introduced legislation in the following years (e.g., Australia in December 1992, Argentina in May 1993, Sweden in 1994, and Norway in 1995).

In addition to the national initiatives relating to the implementation of the protocol, the Transitional Environmental Working Group (TEWG) met at three consecutive Antarctic Treaty Consultative Meetings after the adoption, but prior to the entry into force of the protocol. The TEWG was established in the anticipation and preparation of the entry into force of the protocol, including in particular the establishment of the Committee on Environmental Protection.

Although a number of countries ratified the protocol shortly following its adoption, it nevertheless took a good 6 years before it entered into force. Thirty days following the ratification of Japan, the last country, the protocol entered into force on January 14, 1998.

Today, no country seeking to become a Consultative Party to the Antarctic Treaty can do so without first having ratified the environmental protocol. This requirement is provided for in Article 22 (4) of the protocol.

Further Annexes

Article 9 (2) of the protocol opens for further annexes to be adopted as part of the protocol. The question of protected areas had become an issue already during the protocol negotiations and the outcome of this debate was Annex V on area protection and management, subsequently adopted at ATCM XVI under Recommendation XVI-10. Annex V did not enter into force until May 24, 2002, following the approval of this recommendation by all consultative parties.

At the adoption of the protocol the commitment of the parties to elaborate rules and procedures relating to liability for damage arising from activities taking place in the Antarctic Treaty area had been expressed (also established in Article 16 of the protocol itself) and that work on elaboration of such a regime should begin at an early stage. The XVII Antarctic Treaty Consultative Meeting in Venice in 1992 convened a group of legal experts, under the leadership of Dr. Rüdiger Wolfrum (Germany), to undertake such elaboration. The group presented its report to the XXII Consultative Meeting in 1998. The first round of negotiations on a liability annex was conducted in 1999.

In 2005, at ATCM XXVIII in Stockholm, the negotiations were finalized under the leadership of Ambassador Don Mackay (New Zealand) and an *Annex on Liability Arising from Environmental Emergencies* (Annex VI to the Protocol) was agreed on under Measure 1 (2005). Once this Annex enters into force, an operator active in Antarctica who fails to take "prompt and effective response action to environmental emergencies arising from its activities" shall be liable for the cost of the response action taken by another party.

During the final discussions at ATCM XXVIII several parties noted, however, that Annex VI does not completely discharge the obligations under Article 16 of the protocol. The parties therefore recorded, through Decision 1 (2005), their intention to resume negotiations to elaborate further rules and procedures as may be necessary relating to liability for damage arising from activities taking place in the Antarctic Treaty Area and covered by the protocol.

State of the Environment Reporting

The protocol's Article 12, 1(j) requires that the Committee for Environmental Protection (CEP) provide advice on "the state of the Antarctic environment." The issue of reporting on the state of the Antarctic environment has been an outstanding issue for the parties since the environmental protocol was signed in 1991. A system for reporting on the state of the environment will underpin the environmental principles of the environmental protocol outlined in Article 3, and will provide a useful mechanism for the CEP to fulfil its wider functions (e.g., under Articles 12 1[a], [b], [e], [f], [i], and [k]). A web-based system, the State of the Antarctic Environment Reporting (SAER), for routinely reporting on key environmental indicators, is under development under the auspices of the CEP. The potential value of the SAER comes from its ability to be updated and to provide a central location for recording changes in the status of key indicators over time. Efforts to identify environmental indicators and associated parameters that indicate the impact of human activities in Antarctica and which can be integrated with the SAER system is also ongoing within the CEP.

The Effect of the Protocol

Although the protocol was to a large degree built upon existing regulations and recommendations, it did introduce several fundamental new elements. The protocol approached the question of environmental protection in a *comprehensive manner;* it collected the existing recommendations into a *legally binding instrument;* and it provided for the establishment of a *Committee for Environmental Protection* (CEP) that would oversee the implementation of the protocol's provisions.

As regards Antarctic environmental management, the protocol has served to minimize environmental impacts of human activities in the region by increasing environmental awareness amongst Antarctic operators, inducing transparency of domestic implementation, and providing for mutual control among states regarding environmental practices.

Although the protocol to a large degree has improved environmental management in Antarctica substantially, there are still key issues that remain to be solved. There are still no common standards regarding environmental impact assessments. The assessment of cumulative impact in a multinational/operational environment has proven to be an enormous challenge. There are still unresolved issues of jurisdiction, control, and enforcement, especially regarding activities by third parties, such as tourism. The continued deliberations over the liability question also indicate that there are some major outstanding important environmental issues to be clarified.

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See also **Antarctic Treaty System; Convention on the Regulation of Antarctic Mineral Resource Activities (CRAMRA); Geopolitics of the Antarctic; Tourism**

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PROTOZOA

The correct approach to the classification of protozoa at higher taxa level is still the subject of ongoing debate; however, all the main classically defined groups of terrestrial protozoa (ciliates, flagellates, and both "naked" and testate amoebae) are represented in Antarctica. Within each group the species richness is usually much smaller than that observed in more temperate or tropical areas. For example, within the ciliates (usually considered to be a monophyletic group) a recent review suggested that approximately 15% of soil living species occurred in the Antarctic and sub-Antarctic islands; this contrasted with around 40% for Australia and Tasmania (Foissner 1998). For testate amoebae (which build a "shell," composed of organic matter or material from the environment, that may not be monophyletic), there is a clear trend of reduced species richness with declining mean January temperature when sub-Antarctic sites are compared with those from the maritime or continental Antarctic (Smith 1996). Similar patterns are probably present in other protozoan groups, but their biogeography within the Antarctic has not been studied in as much detail as the testate amoebae.

The main reason for the low species richness of Antarctic protozoa is probably the severity of the climate; the role of constraints on dispersal in the biogeography of polar protozoa is currently controversial but seems very likely to also be of importance (Wilkinson 2001). Most areas of the Antarctic are likely to have been recolonised by protozoa since the last glaciation, that is, within the last 10,000 years. It is also clear that knowledge of Antarctic protozoa is as yet incomplete; for example, in a study of ninety soil samples from Antarctica, Foissner (1997) estimated that 15% of the ciliate taxa found were undescribed species.

As well as reduced species richness, many of the Antarctic protozoa are usually recorded as having low population densities; one important exception to this generalization is protozoan communities in the guano of marine birds (Smith 1996). In Wilkes Land, Eastern Antarctica, the highest abundances of both ciliates and testate amoebae were recorded from Moss samples (Petz 1997); in general, substrates with higher organic matter content tend to support more protozoa. Studies of the population ecology of soil testate amoebae on South Georgia found that they showed rapid population growth rates (in excess of 5% per day) during the spring (Smith and Headland 1983).

Over the next few decades it is likely that global warming will have a major impact on Antarctic ecology. Because of their short generation times and small size (and hence presumed ease of dispersal), it has been suggested that distribution changes in Antarctic protozoa may provide a sensitive indication of the biological effects of climate change. For example, the soil ciliate *Colpoda* spp. has been suggested as a useful indicator species for the effects of climate change in the Antarctic (Smith 1996; Smith and Crook 1995).

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See also **Microbiology; Mosses; South Georgia**

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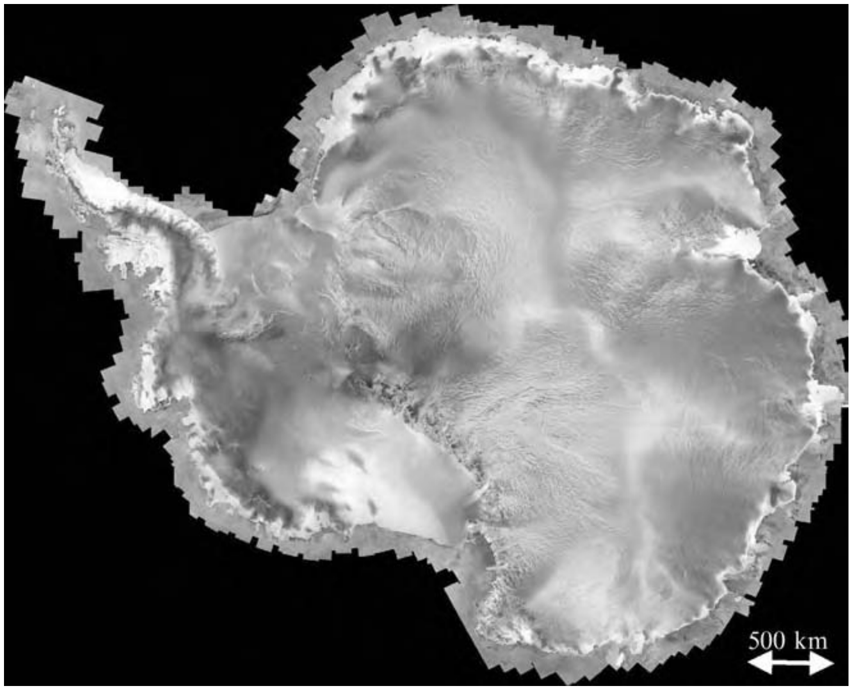
RADARSAT ANTARCTIC MAPPING PROJECT

Shrouded in darkness during the austral winter and often obscured from view by persistent cloud cover, Antarctica remained one of the most poorly mapped parts of our planet. That changed in 1997 when the Antarctic Mapping Mission-1 (AMM-1) project began to scan Antarctica from space. This was made possible by the Canadian RADARSAT-1 satellite, which carries a C-band (5.3 GHz) Synthetic Aperture Radar (SAR) capable of acquiring high resolution (25 m) images of Earth's surface day or night and under all weather conditions. RADARSAT-1 also collects data using a variety of swath widths, incidence angles, and resolutions, and, most importantly for scientists interested in Antarctica, it was maneuvered in orbit to rotate the normally right-looking SAR to a left-looking mode. This "Antarctic Mode" provided the first, nearly instantaneous, high-resolution views of the entirety of Antarctica.

The goal of the RADARSAT Antarctic Mapping Project (RAMP) was to create the first, high-resolution, radar image of the continent. The resulting map now serves as a benchmark for gauging future changes in the polar ice sheet, enables deeper understanding of the behavior of the glacier and its interaction with the polar atmosphere and coastal ocean, and simply expands our ability to explore the vast, remote, and often beautiful, southernmost continent (Jezek 1999; Liu and Jezek 2004).

AMM-1 contingency acquisitions began seven days prior to the start of the nominal acquisition plan. Nominal acquisitions started on schedule shortly after noon Eastern Standard Time on September 26, 1997. The nominal plan was designed to obtain complete mapping coverage within 18 days from the coast to the South Pole and it proceeded nearly flawlessly through completion on October 14. An additional opportunity was realized because of the early start on September 19. Radar data collected after the conclusion of the nominal mission were acquired exactly 24 days after the beginning of the early start data. This schedule repositioned the spacecraft to within a few hundred meters of its position 24 days earlier. Consequently, the data are suitable for interferometric analysis—a demonstrated technique for estimating ice sheet surface displacement. Exact repeat data collections started on October 14 and continued through October 20.

The RAMP mosaic is assembled from about 4500 radar scenes and is truly a new view of Antarctica. Evident in the mosaic are large-scale spatial variations in radar brightness. The bright portion of Marie Byrd Land and the eastern sector of the Ross Ice Shelf represent regions where significant melting and refreezing occurred during an early 1990s melt event. Most of the coastal areas and much of the Antarctic Peninsula also appear bright because of summer melt. But, unlike Greenland, where most of the large-scale brightness patterns are associated with firn melt faces, the remaining strong variations in radar brightness are more likely associated with changing patterns in surface accumulation rate. At a somewhat smaller scale, thousands-of-kilometers-long curvilinear features



RADARSAT-1 SAR mosaic of Antarctica. The map is a polar stereographic projection with standard latitude of 71° S and is referenced to the WGS84 ellipsoid. Light shading indicates strong backscatter. Dark shading indicates weak backscatter.

snake across East Antarctica. These appear to follow ice divides separating the large catchment areas (Liu et al. 1999). The reason that the ice divides appear so prominently in the radar imagery is unknown.

On an intermediate scale, the East Antarctic Ice Sheet appears to be very "rough." The texturing is probably due to the flow of the ice sheet over a rough glacier bed. Textures are particularly strong parallel to the flanks of the Transantarctic Mountains and extending deep into adjacent portions of the East Antarctic Plateau. Long linear patterns are strongly suggestive of subglacial geology and may indicate that the ice sheet in this area is resting on relatively resistant basement rocks. The texture changes abruptly across the northernmost section of the Wilkes Subglacial Basin located in George V Land. There, the imagery shows remarkable, subtle rounded shapes similar in appearance to the signature of subglacial lakes such as Lake Vostok.

Most intriguing are ice stream and ice stream-like features in Queen Maud. Ice streams are made visible by the intense crevassing along the shear margins where chaotic surface roughness results in a strong radar echo. Fast, channeled flow, which are two of the diagnostic characteristics of ice streams, are evident in the surface velocity field computed from repeat pass interferometry (described in the next section). Slessor Glacier is located on the northeastern margin of the Filchner Ice Shelf. The upper reaches of the glacier consist of a network of tributaries that feed a funnel shaped midsection. Patches of crevasses punctuate the interior of the funnel. The ice stream is about 450 km long from the grounding line to the upstream area.

An enormous ice stream, reaching at least 800 km into East Antarctica, feeds Recovery Glacier. It too is fed by a funnel shaped catchment. Down-glacier, crevasses cascade across the ice stream at several locations suggesting that strong variations in basal topography modulate the flow. The confluence of a thin, elongated, 280 km long tributary ice stream with Recovery Glacier is located approximately 250 km from the constriction where Recovery Glacier enters the Filchner Ice Shelf. The central body of the pipe-like tributary is crevasse-free, indicating that shear stresses are concentrated only at the margins. The tributary is an enigma in that there is little evidence for ice flow into the tributary from the adjacent ice sheet and there is little, if any, indication as to the source of ice from the up-glacier catchment region.

During the early 1990s, researchers at the Jet Propulsion Laboratory showed that synthetic aperture radar (SAR) offered a revolutionary new technique for estimating the surface motion of glaciers (Goldstein et al. 1993). Known as radar interferometry, multiple observations of a site are used to obtain very precise estimates of surface displacement. The demonstration of this technique for SARs in general and the demonstration during AMM-1 that the technique worked for RADARSAT-1 in particular (Joughin et al. 1999; Gray et al. 2001; Gray et al. 2002) were the impetus for the Modified Antarctic Mapping Mission (MAMM), which occurred during the fall of 2000.

MAMM had two primary science objectives (Jezek 2002). The first was to remap the perimeter of the continent and the majority of Antarctica's fast moving glaciers. Intuitively, these are the areas that are most likely to have experienced change over the intervening three years. The second MAMM objective was more ambitious—to obtain as much surface velocity data on the ice sheet as possible. Measurements of Antarctic ice sheet surface motion are of keen interest to geoscientists. The rate and direction of motion reveals important information about the forces acting on the glacier, provides knowledge about the rate at which ice is pouring into the coastal seas, and enables scientists to predict how the ice sheet might respond to changing global climate.

MAMM acquisitions were planned in two ways to attain these goals. First, data were acquired so that, where possible, the position of structures on the glacier could be compared between the 1997 and 2000 data sets so as to measure point velocities (Jezek et al. 2003). Second, and the real challenge of MAMM, was to acquire interferometric data to estimate velocity fields. The second approach required the use of RADARSAT-1 fine and standard beams, and unprecedented control of the spacecraft orbit and attitude. The outcomes of this effort are extraordinary observations of glacier motion captured over three 24-day RADARSAT cycles.

Interferometrically derived data acquired over the David Glacier and the Drygalski Ice Tongue located in Northern Victoria Land, Antarctica serve as an example of MAMM surface velocities. The ice tongue is a long, relatively narrow, extension of David Glacier onto the Ross Sea. Near the coast, several small outlet glaciers flank the David Glacier, which itself is fed by a system of tributaries. Surface speeds derived from MAMM interferometric data increase from about 100 m/yr in the upstream portions of David Glacier to about 750 m/yr at the tip of the Drygalski Ice Tongue. The Drygalski Ice Tongue has been studied since the early 1900s. Holdsworth (1985) compared historical, airborne photographic and Landsat data to estimate a velocity of 730 m/yr ± 36 m/y for a point 50 km from the coast. This is similar to the MAMM result of 710 m/yr ± 10 m/y to within the estimated errors. Several other investigators analyzed sequential Landsat scenes by coregistering images with tie points. The MAMM result at the landward end of the velocity profile (578 m/yr) compares favorably with Swithinbank's (1988) estimate of 580 m/yr but less than Lucchitta and others' (1993) estimate of about 640 m/yr. The MAMM maximum value (755 m/yr) is similar to 15-year average-maximum velocities (719 m/yr over 1973–1988) quoted by Frezzotti (Frezzotti 1993; Frezzotti et al. 2000) but less than Lucchitta and others (1993) whose estimated 15-year average velocities (1973–1988) near the tip are approximately 800 m/yr. The MAMM maximum values are also less than Frezzotti's 13-month average-maximum velocity of 912 m/y (1988–1990). Frezzotti and others (1998) compare their Landsat derived velocities with Global Positioning system data collected on the ice tongue. They find that the GPS velocities agree with the Landsat feature retracking data on the landward half of the ice tongue.

RAMP demonstrated the technical capability to acquire nearly instantaneous high-resolution microwave imagery of the entire Antarctic continent. The technical achievement is being followed by an unfolding scientific examination that is revealing the glaciology and geology of Antarctica in unexpected detail. As importantly, the acquisitions provide an important benchmark for gauging and understanding future changes in the Antarctic Ice Sheet.

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See also **CryoSat; Icebergs; Glaciers and Ice Streams; Ice–Rock Interface; Ice Sheet Modeling; Ice Shelves; ICESat; Lake Vostok; Mega-Dunes; Remote Sensing; Ross Ice Shelf; Subglacial Lakes; Thwaites and Pine Island Glacier Basins**

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REMOTE SENSING

Introduction

Over the past 30–40 years, satellite and other remote sensing methods have provided an immense wealth of new data to revolutionise understanding of the Antarctic. While important, field measurements are logistically challenging, expensive, and sparse. Satellites alone can measure and monitor remote and vast areas in a sustained, consistent, systematic, repetitive, and cost-effective fashion and on a variety of scales. Remote-sensing systems used fall into two broad categories: active and passive. Active systems (e.g., radars and lasers) transmit electromagnetic energy towards the surface and record the time interval, intensity, and characteristics of the return echo scattered (reflected) back. Passive systems sense naturally occurring radiation (e.g., reflected solar or emitted thermal). Earth-observing sensors operate at wavelengths/frequencies corresponding to "atmospheric transmission windows" in the electromagnetic spectrum, within which atmospheric contamination effects are minimised. Sensors operating outside such windows provide key information on the vertical structure/characteristics of the atmosphere itself. In all cases, polar-orbiting rather than geostationary satellites are most useful; as the latter sit at points ~37,000 km above the Equator, their coverage of Antarctica is geometrically distorted and limited, although they provide useful information on cloud/weather patterns over peripheral seas.

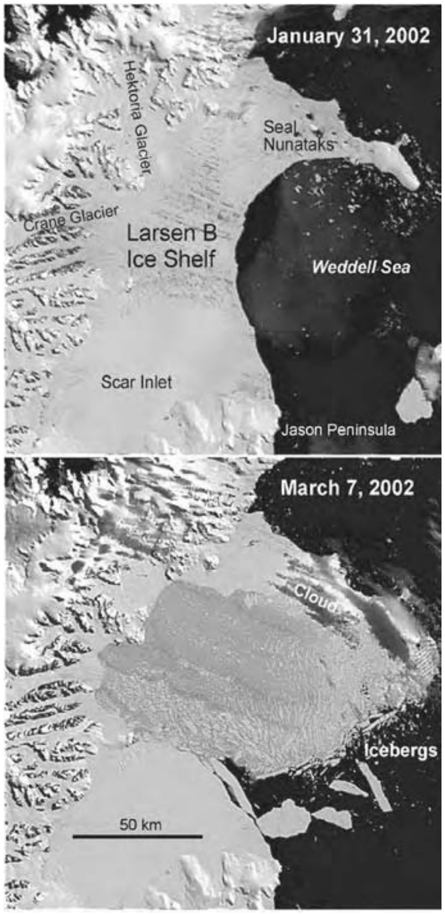
Passive Remote Sensing

Optical to Thermal Infrared (OTIR) Radiometers

Satellite detectors operating at optical wavelengths measure reflected solar radiation in the spectral region 0.4 to 3.0 μm. This comprises the visible (0.4–0.70 μm) and reflected infrared or IR (0.70–3.00 μm), with the near-IR and middle (shortwave) IR occupying the 0.70–1.30 μm and 1.30–3.00 μm bands, respectively. Being reliant on sunlight, these sensors are ineffective during periods of darkness—a major limitation in polar regions. Another limitation is their inability to "see" through clouds, although they yield important information on cloud fraction/type.

Broadly speaking, sea-ice spectral reflectance (ratio of radiant energy reflected by a body to that incident upon it) depends upon its age and thickness, and the presence/absence of a snowcover. Snow reflectance depends on the refractive index of ice, grain-size distribution, density, depth, and liquid-water content. Maps of surface albedo (the ratio of upwelling to downwelling radiative flux at the surface) can be retrieved from satellite radiance data after accurately masking cloud, correcting atmospheric effects, and converting angular measurements to the "full hemisphere" angular distribution of the surface (the bidirectional reflectance distribution function [BRDF]). While the broadband albedo of ice-free ocean is ~0.05–0.1, that of sea ice ranges from ~0.1 to ~0.9, enabling ice-ocean discrimination and ice-type classification. The strong sensitivity of near-IR radiation to snow grain-size growth with melting further enables the detection/monitoring of seasonal melt/refreeze. Ice-sheet surface grain size is itself retrievable from 1.6 μm data (e.g., from the Global Imager [GLI] aboard ADEOS-II [operational from 2002–2003]).

The basis of thermal infrared (TIR) remote sensing is that every object with a physical temperature >0 K



The extraordinary disintegration of the Larsen B Ice Shelf captured in NASA MODIS imagery. (Imagery courtesy Ted Scambos [US National Snow and Ice Data Center], acquired from the NASA Visible Earth website [http://visibleearth.nasa.gov/].)

thermally emits radiation that can be recorded by radiometers operating in the 3–15 μm region, and typically exploiting atmospheric-transmission windows at 3–5 μm and 8–15 μm. Data from the 3–5 μm region contain both solar-reflected and thermally emitted contributions, and are most commonly used to distinguish clouds from snow/ice during daylight hours. Thermal radiation, mainly 8–15 μm, emitted by objects as a function of their physical temperature and emissivity μ (the ratio of the radiation emitted by an object to that emitted by a blackbody [perfect radiator] at the same temperature). It follows that maps of skin-surface temperature can be derived from cloud-free TIR data, with knowledge of μ (which approximates unity at these wavelengths) and atmospheric contributions. The latter are typically minimised by differencing data from spectrally adjacent channels with different absorption responses to water vapour (e.g., band 4 [10.3–11.3 μm] and band 5 [11.5–12.5 μm] of the NOAA Advanced Very High Resolution Radiometer [AVHRR]). Other important applications include the detection/mapping of surface features/ice distributions during polar darkness, and sea-ice classification based upon thermal variation due to ice thickness (for thin ice). Much again depends upon accurate cloud detection and masking—a major challenge given the similarity in reflective and thermal properties of snow/ice and clouds.

Spaceborne OTIR missions can be divided into the following categories:

- *Moderate-resolution sensors,* with a spatial resolution of 0.25–4 km and swath width of ~1500–2800 km, offer virtually complete polar coverage on a daily basis. Primary examples are the NOAA AVHRR (1978–present), the Optical Linescan System (OLS) aboard Defense Meteorological Satellite Program (DMSP) satellites (1979–present), Moderate-resolution Imaging Spectro-radiometers (MODISs) aboard the NASA satellites Terra (1999–present) and Aqua (2002–present), the Medium Resolution Imaging Spectrometer (MERIS) aboard ESA's Envisat (2002–present, lacking TIR channels), and Visible/Infrared Imager Radiometer Suite (VIIRS) sensors aboard National Polar Orbiting Environmental Satellite System (NPOESS) satellites (from 2006). Near real-time availability has led to dramatic discoveries, including the disintegration of the Larsen B Ice Shelf in early 2002 and the calving of immense icebergs from the Ross Ice Shelf. Major products are large-scale maps of surface temperature and albedo. Other applications include sea ice motion from sequential imagery using cross-correlation techniques, mapping of fast ice, ice-sheet morphological features and coastal configuration, and enhanced-resolution ice-sheet digital elevation models (DEMs) using photoclinometric processing (shape-from-shading) techniques. A subgroup are *ocean-colour sensors,* which measure subtle variations in the colour of near-surface, ice-free waters. The magnitude of primary production can be derived from this information, based on the amount of solar radiation absorbed by phytoplankton chlorophyll in the upper-water column. Important current sensors are the OrbView-2 Sea-viewing Wide Field-of-view Sensor (SeaWiFS, 1997–present), MERIS and MODIS, with VIIRS in future. Major discoveries have related to the close association between sea ice distribution and phytoplankton blooms.

- *High-resolution sensors* acquire data over a narrow swath (<200 km) with a nominal repeat cycle of 16–26 days, and a spatial resolution of ~5 to <100 m. Current commercial examples include the Enhanced Thematic Mapper Plus (ETM+) on Landsat-7 (1999–present), and the High-Resolution Geometric (HRG) and High-Resolution Stereoscopic (HRS) sensors aboard SPOT-5 (2002–present). While SPOT sensors offer higher resolution than Landsat and to a higher latitude (~86° versus ~82.5°), Landsat scene coverage is greater (i.e., 185 × 185 km versus 60 × 60 km). Moreover, SPOT sensors (1986–present) lack the nighttime viewing capability of modern Landsat TIR channels. Non-commercial examples include the EOS Terra Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER) and the Advanced Visible and Near-Infrared Radiometer-2 (AVNIR-2) on the Japanese Advanced Land Observing Satellite (ALOS, launch 2005). This sensor class is best suited to studies requiring localised detailed coverage. While sea-ice applications are largely limited to the validation of coarser-resolution data, Landsat in particular has made a major contribution to ice-sheet research (since 1972) (e.g., in the production of high-density maps of ice velocity by measuring temporal displacement of conspicuous features [e.g., crevasses], and mapping/monitoring of ice-sheet morphology/margins [many subtle morphological features which cannot be identified at ground level are readily apparent from space]).
- *Ultra-high-resolution optical sensors* provide images at a spatial resolution of <1 m to <5 m but over narrow scenes of <20 km (limiting polar applications to very detailed localised studies). Commercial examples include Ikonos-2 (launch 1999), Quickbird-2 (2001), and EROS-A1 (2001). SPOT-5 has a 2.5 m resolution mode with wider coverage (60 km). Declassified Intelligence Satellite Photography (DISP) imagery, in hard-copy format and dating back to 1962, became available in 1995. The limited number of cloud-free scenes available provide tantalising glimpses of past conditions, and have been combined with modern imagery to monitor change (e.g., in glacier and ice-sheet margins).
- *Multi-angle sensors* record near-simultaneous observations of the same point from multiple angles during a single data acquisition. Examples are the Envisat Advanced ATSR (AATSR), the ASTER, and the Multi-angle Imaging Spectro-Radiometer (MISR, 1999–present). The latter operates four bands in the visible to near-IR (360 km swath, spatial resolution 270 m). Information on reflectance change at different view angles affords enhanced surface discrimination and improved surface-albedo retrieval by enabling more complete characterization of the surface BRDF. Both the MODIS and MISR spectro-radiometers also provide more precise measurements of cloud features at higher resolutions than before to greatly benefit climate research.
- *Hyperspectral sensors (imaging spectroscopy)* simultaneously acquire images in many narrow and contiguous spectral bands, to construct a complete reflectance spectrum for each pixel. The first spaceborne hyperspectral sensor, the EO-1 Hyperion Imaging Spectrometer (launch 2000), acquired measurements across 220 calibrated spectral bands in 10 nm bandwidths (from 0.4 to 2.5 μm) with a 10–30 m resolution, but over a narrow (7.5 km wide) swath. While of limited Antarctic applicability, such data show potential for improved though localised estimates of surface optical albedo, snow-grain size, and sea-ice classification.

Passive Microwave Radiometers

With excellent wide-swath coverage uninterrupted by clouds/darkness, satellite passive-microwave (PMW) radiometers are the primary source of information on Antarctic sea-ice concentration and extent. They measure the intensity of naturally emitted thermal radiation from the surface, in a similar fashion to thermal infrared radiometers but at much longer (i.e., centimetre) wavelengths. Their ability to detect sea ice is based upon the strong microwave-emissivity contrast between ice and ocean under freezing conditions (e.g., ~0.94 versus ~0.34 respectively at 37 GHz [horizontal polarization]). Polarization describes the locus of the electric-field vector in the plane perpendicular to the direction of propagation. Current sensors are the DMSP Special Sensor Microwave/Imager (SSM/I, 1987–present) and Aqua Advanced Microwave Scanning Radiometer (AMSR-E, 2002–present). While the spatial resolution of sea-ice products is poor (12.5–25 km), complete daily polar coverage is possible. Dating back to 1973, this unique dataset is widely applied to analyses of sea-ice trends/variability and process studies. The real-time downloading of satellite PMW data by modern icebreakers and research vessels has resulted in safer navigation and immense fuel savings. Other important applications include routine mapping of sea-ice temperature and snow-depth with AMSR-E data, sea-ice motion, and polynyas. Future coverage with the NPOESS Conical-scanning Microwave Imager/Sounder (CMIS, starting in 2009) includes an additional atmospheric-*sounding* capability. By operating at frequencies around spectral bands characteristic of target gases (e.g., 60 GHz and 183 GHz), microwave sounders measure the vertical profiles of atmospheric temperature and moisture.

Over cold dry ice sheets, PMW radiometers provide information on surface and near-surface properties, with microwave emission being determined by snow/firn temperature, layering, density, grain size/shape, and surface roughness. A research-and-development product is ice-sheet accumulation rate, based on its physical relationship with microwave emission as affected by depth-dependent grain-size distributions. As snow/firn emissivity is highly sensitive to liquid water, PMW data also provide key information on interannual variability in the timing/extent of seasonal surface melt and freeze-up (both pack ice and ice sheet).

Active Remote Sensing

Radars transmit a microwave signal then measure the reflection back from the target object as a function of frequency (wavelength), polarization, and incidence angle, again unaffected by cloud and darkness. The strength of the radar return (backscatter) is determined both by surface electrical properties and geometric characteristics. Significant microwave penetration into snow/ice can yield additional information on structural/internal properties.

Synthetic Aperture Radar

First launched on Seasat in 1978, the Earth-observing spaceborne synthetic aperture radar (SAR) is a powerful operational and research tool. SARs differ from spaceborne real-aperture radars (e.g., aboard Russian Kosmos Okean satellites, which are limited to a ground resolution of $\sim$1–2 km), by exploiting the satellite's along-track motion to computationally synthesise a large antenna and increase the resolution to tens of metres. Coverage is over a relatively narrow swath of 75–500 km. Key missions include ERS-1 (1991–2000), ERS-2 (1995–), JERS-1 (1992–1998), Radarsat-1 (1995–) and –2 (launch 2006), Envisat (2002–), the Advanced Land Observing Satellite (ALOS, 2005–), and in the future TerraSAR-X (launch 2006) and –L (launch 2007).

SAR provides all-weather high-resolution imagery of radar backscatter with which to map and interpret surface and near-surface characteristics. Clear feature-delineation is possible over ice sheets due to the radar's sensitivity to subtle variations in grain size, local relief, surface roughness, and moisture content. Major applications include mapping/monitoring of large-scale zones of different snow and ice diagenesis ("facies"), and seasonal/inter-annual patterns of melt/refreeze. An important product is the first high-resolution "snapshot" map of the entire Antarctic Ice Sheet by the Radarsat-1 Antarctic Mapping Mission (AMM-1). Main sea-ice applications are ice-type classification and open water-thin ice discrimination, ice motion/deformation, fast-ice extent, wave-ice interaction, seasonal melt/freeze-up detection, ice-edge characteristics, and wind speed and direction, and iceberg detection and tracking—a powerful combination. Overall limitations include the high data volume and relative complexity of interpretation. Although SARs are generally unsuited to routine large-scale coverage, reduced-resolution data have recently become available in near-real time from the Envisat Advanced SAR operating in Global Monitoring Mode (1 km resolution over a 400 km swath).

Extraordinary discoveries have recently resulted from interferometric processing of SAR imagery. SAR interferometry (InSAR) combines coherent image pairs acquired by antennae at different times and/or slightly different locations to construct interferograms (maps of phase difference). This enables detection of small (centimetre-scale) differences in range to a surface target from two (or more) observation points, from which high-resolution surface change/motion and topographic maps can be constructed. Although the availability of suitable image pairs is limited by temporal surface decorrelation over the period separating image acquisitions (for repeat-pass systems), InSAR has provided a wealth of new information on ice-sheet mass balance and dynamics. Uniquely, it has the capacity to acquire high-density ice-motion data in featureless expanses (where conventional feature-tracking techniques fail). It can also resolve glacier/ice stream surge behaviour and grounding-line location and migration, the latter by virtue of its sensitivity to vertical tidal motion of floating ice shelves/glaciers. Much-improved estimates of net mass budget and ice-shelf basal melt rates have resulted. To date, suitable InSAR data have come mainly from the ERS Tandem Mission (1995–1996), when ERS-1 and -2 flew in identical orbits but one day apart. No dedicated satellite InSAR system has been launched to date, although a tandem Radarsat-2 and -3 mission is planned. An alternative technique, speckle tracking, has been devised to derive ice-velocity data in fast-flowing regions (where InSAR processing fails). This exploits the cross-correlation function of speckle patterns (noise-like characteristics) in pairs of real-valued SAR-amplitude images, and is also suitable where the time interval between images is large (e.g., the 24-day repeat interval of Radarsat-1). Maximum-coherence tracking is similar, but uses phase information.

Another exciting development is the launch of satellite SARs with multipolarization (e.g., Envisat ASAR) and full-polarimetric capability (e.g., ALOS Phased Array L-band SAR [PALSAR] and advanced SARs aboard TerraSAR-X/-L and Radarsat-2). These systems not only receive the transmission polarization and its orthogonal, but can also record phase differences between different polarization combinations. Sensors with full-polarimetric capability can simultaneously acquire backscatter-amplitude data at HH, VV, HV, and VH polarizations, while also measuring relative phase between channels. This provides the potential to significantly improve sea-ice classification (particularly for thin-ice types) and ice-water discrimination under windy conditions, as well as the detection of ice-sheet facies and related boundaries. Another emerging technique is POLInSAR, or the melding of SAR polarimetry and interferometry. This shows potential as a means of enhancing the discrimination of polar surface types, by enabling more complete separation of surface- and volume-scattering effects and contributions.

Radar Scatterometers

Although primarily designed to measure wind velocity over open ocean, radar scatterometers also provide important information over ice-covered surfaces. Their strength lies in their excellent wide-swath coverage, low data rate, near-real time availability, all-weather, day/night operation, near-daily complete polar coverage, and a continuous time series of stable and accurately calibrated data dating back to 1991. Although their nominal spatial resolution is poor (i.e., 25–50 km), it has been improved by recent processing advances. Important missions include the Seasat-A Scatterometer (SASS, 1978), ERS-1 (launch 1991), ERS-2 (launch 1995), the NASA Scatterometer (NSCAT) aboard ADEOS-I (1996–1997), and SeaWinds on QuikSCAT (1999–present) and ADEOS-II/Midori-2 (2002–2003), with the Advanced Scatterometer (ASCAT) on MetOp in 2005. Radar scatterometers are well-suited to the mapping of regional-to-hemispheric patterns of melt/freeze-up, ice-sheet facies and operational monitoring of sea-ice motion and extent and large-iceberg tracking. Other applications include inference of mean surface wind-field direction over the ice-sheet interior (based upon their sensitivity to snow-dune orientation), empirical determination of ice-sheet accumulation patterns, and mapping of different sea ice-type regimes.

Radar Altimeters and LASER Altimeters

Radar altimeters transmit short pulses of electromagnetic radiation towards the surface at nadir, then measure the reflected energy. With precise knowledge of the satellite position, the recorded time-delay between pulse transmission and receipt provides a measure of ice-sheet surface elevation along the satellite ground track. These data have enabled the construction of high-resolution DEMs to revolutionise ice-sheet dynamics modeling, and the measurement of surface-elevation changes over periods of 5–10 years. Recent discoveries include a major thinning trend of -11.7 ± 1.0 cm a^{-1} over the Pine Island-Thwaites Glaciers drainage basin (West Antarctica) from 1992–1996 using ERS-1 and -2 data.

While early altimeters (e.g., Seasat [1978] and Geosat [1985–1990]), were designed for open-ocean operation, modern altimeters (e.g., aboard ERS-1 and -2 and Envisat), include an "ice mode" of operation to provide more precise measurements over ice. These altimeters perform well over relatively smooth ice-sheet interiors, but less so over more variable/steeper terrain (e.g., around ice-sheet margins). This led to the development of two innovative new spaceborne systems, namely ICESat and CryoSat. With coverage to 86° S and launched in January 2003, the Geoscience Laser Altimeter System (GLAS) on NASA's ICESat is a range-measuring device similar to radar but transmitting pulses of light—in this case at 1.064 μm (for altimetry) and 0.532 μm (for measuring cloud and aerosol vertical distributions). Advantages include a smaller surface footprint ($\sim$60 m) and along-track spacing ($\sim$172 m), and minimal signal penetration into the snow/ice mass to enable much-improved measurement of ice-sheet margins (to an unprecedented accuracy of $<$1.5 cm a^{-1}). A major limitation compared to radar is its inability to penetrate cloud cover. Another objective is measurement of sea-ice thickness, surface roughness, and surface reflectivity. CryoSat was designed to exploit sophisticated radar techniques to enhance resolution and observing capabilities, thereby providing improved estimates of ice-sheet thickness changes and sea-ice thickness. Unfortunately, CryoSat failed to enter orbit due to a launch malfunction in early October 2005.

Gravity Missions

Launched in March 2002, the joint US-German Gravity Recovery and Climate Experiment (GRACE) is the first in series of missions devoted to measurement of the Earth's time-variant gravity field, the others being GOCE (the Gravity field and steady-state Ocean Circulation Explorer, launch 2005) and the GRACE-FO (Follow-On, launch 2007). Gravity measurements are sensitive to changes in mass under the satellite, including mass redistribution due to crustal uplift and mantle inflow and changes in the mass of snow/ice contained in the ice sheet. Used in concert with ICESat, GRACE provides an important new constraint on contemporary total mass-imbalance estimates, to enable estimates of ice sheet–related contributions to global sea-level change to an unprecedented accuracy of $\sim$0.2 mm a^{-1}.

Aircraft and Field Measurements

Satellites also play a major role in transmitting information from sensor packages deployed on the surface (e.g., automatic weather stations and ice beacons/buoys), in the ocean (e.g., Argo floats), and attached to birds and mammals. Remote autonomous vehicles (underwater and airborne) gather oceanographic information unattainable by spaceborne sensors (e.g., under-ice ocean conditions/properties, ocean fluorescence, and water chemistry). Ice-draft measurements are acquired by long-term arrays of moored upward-looking sonars (ULSs), for conversion into point ice-thickness estimates. Sea-ice thickness profiles have also been acquired by helicopter- and ship-borne electromagnetic induction (EMI) sounding, which exploits the marked contrast in sea-ice and seawater electrical conductivities to detect the ice-water interface, with surface-elevation measurements provided by laser-altimeter data. Work is underway to develop low-frequency (300–1300 MHz) radar systems for measuring sea-ice thickness from aircraft. Surface and aircraft campaigns remain essential to both validate/calibrate satellite data/products and provide information currently unattainable from space (e.g., ice-sheet vertical flow characteristics and absolute grounded-ice thickness). Measurement of the latter can only be carried out by surface/airborne radio-echo sounding, or ice-penetrating radar, which also provides a means of tracking internal layers related to past ablation/accumulation conditions.

ROBERT A. MASSOM

See also **Antarctic Peninsula, Glaciology of; Clouds; CryoSat; Firn Compaction; Glaciers and Ice Streams; Ice Shelves; Icebergs; ICESat; Larsen Ice Shelf; Mega-Dunes; Pack Ice and Fast Ice; Polynyas and Leads in the Southern Ocean; RADARSAT Antarctic Mapping Project; Ross Ice Shelf; Sea Ice: Microbial Communities and Primary Production; Sea Ice: Types and Formation; Snow Post-Depositional Processes; Thwaites and Pine Island Glacier Basins**

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REPRODUCTION

Antarctic seas are usually viewed as being among the harshest environments on Earth: perpetually cold, freezing over and thawing annually, and continually dark for months each year, restricting food production. Such an environment would be expected to generate unusual adaptations in the biology of the animals living there, including their reproduction. On the other hand, being constantly cold is at least a constant; in temperate and even tropical seas wide temperature swings can dominate life. Moreover, the ice cover dampers disruptive storms, making the environment relatively benign (in winter) and especially favorable for life. Both of these views have validity, as seen in different benthic inhabitants of Antarctic waters.

In shallow water, less than 30 m deep, ice forms seasonally on the bottom around the Antarctic continent, and small icebergs occasionally scour the bottom. The biota in these areas is in a constant state of flux. Some of the animals (sea stars, sea urchins, scallops, worms, fishes) are mobile and so can take advantage of the relatively high productivity in the summer while evading ice damage in the winter. In contrast, the environment in deeper water is unusually calm and undisturbed over very long periods, but varies from place to place with respect to food supply from overlying waters. Areas that receive abundant seasonal food are often biologically complex and diverse, comparable with other diverse marine ecosystems in the world, with dense communities of sponges, soft corals, bryozoans, and other sessile animals. More food-limited areas, covered with thick layers of ice that inhibit productivity, are less complex but may still have a high diversity of small animals, perhaps most comparable to that in the equally stable but food-limited deep-sea.

In the shallow, seasonally rich but disturbed habitats, most animals have reproductive modes similar to their counterparts in other parts of the world. They are mainly gonochoric: separate males and females spawn seasonally, releasing large numbers of small gametes that develop into feeding (planktotrophic) larvae. Such larvae are capable of wide dispersal to distant recently disturbed areas where they can settle and grow into adults with limited risk from competition and predation. In contrast to temperate and tropical species, however, Antarctic species display extremely slow gametogenesis, development, and growth, probably a consequence of low temperature and low food supplies during most of the year. Current work is being done on two of these species: the sea star *Odontaster validus* and the sea urchin *Sterechinus neumayeri*. Both are abundant and easy to rear in the laboratory, and they are excellent for the studying metabolism and development at freezing temperatures.

The biologically complex deeper communities, with extensive cover of sessile, suspension-feeding animals, are more challenging for incoming larvae. Just finding a place to settle is a problem, as well as avoiding being eaten or overgrown by competitors. Most animals in deeper Antarctic communities meet these challenges by producing relatively few but large eggs that develop into large pelagic larvae, and after more limited dispersal, settle as large, more competitive juveniles. This mode of development occurs not only in sessile animals such as sponges and soft corals, which produce large nonfeeding larvae around the world, but also in the sea stars that feed mainly on the sponges and soft corals. Two well-studied examples are the sea stars *Acodontaster hodgsoni* and *Porania antarctica.*

In addition to the putative adaptive value of producing relatively few but large nonfeeding larvae that can recruit into biologically complex communities, there may be historic reasons for the high proportion of nonfeeding larvae in Antarctic waters relative to other seas. During glacial maxima, extensive, thick ice sheets probably extended out over the continental shelf, effectively blocking sunlight year round and severely reducing phytoplanktonic food for feeding larvae. One theory is that during such times, selective extinction of species with feeding larvae could have resulted in the disproportionate number of species with nonfeeding larvae that is seen today.

In addition, some groups (clades) of animals in Antarctic waters are unusual because they produce no pelagic larvae at all; instead, the embryos are either retained (brooded) on or in the mother's body or placed in benthic capsules, where they develop directly into juveniles, bypassing the larval stage. Heart urchins (e.g., *Abatus* spp.) and pencil urchins (e.g., *Ctenocidaris* spp. and *Notocidaris* spp.) are good examples of brooding species that are unusually abundant in Antarctic waters. This mode of development is found in a large variety of animals around the world; what is unusual in the Antarctic is the relatively large number of closely related species, all of which brood, especially among echinoderms and molluscs. Nineteenth-century expeditions noted this phenomenon, and in the mid-twentieth century the Danish marine biologist Gunnar Thorson promoted the idea ("Thorson's Rule") that all polar and deep-sea benthic invertebrates had nonpelagic development as an adaptation to conditions thought to be unsuitable for pelagic, feeding larvae.

Though it is now known that Thorson's Rule is incorrect, the species-rich clades of brooding echinoderms and molluscs remain nearly unique to Antarctic and sub-Antarctic habitats and demand to be explained. One plausible explanation is the unusually favorable conditions for speciation that are provided by the Antarctic Circumpolar Current. This current has been flowing through Drake's Passage for ~30 million years. Brooding individuals could be picked up infrequently from the bottom, particularly during volcanic activity and earthquakes, and transported to new habitats. Because they retain their offspring, and produce no larvae to get carried away, they would be immediately isolated reproductively, and could readily evolve into new species in their new habitats. That would not happen if there was a constant input of new larvae from distant habitats. Such events would not have to happen often over the past 30 million years for numerous closely related species to accumulate in the nearly unchanging Antarctic marine environment. This hypothesis, accounting for the unusual species-rich clades of animals with nonpelagic development in Antarctic waters, remains tentative and must be further explored using modern cladistic approaches and a long-term geologic perspective, but it provides the basis for further study.

John S. Pearse

See also **Benthic Communities in the Southern Ocean; Circumpolar Current, Antarctic; Deep Sea; Larvae; Molluscs**

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RESTORATION: SUB-ANTARCTIC ISLANDS

Restoration is a community phenomenon: an attempt to reproduce exactly the entire community that had been present before some disturbance. Such disturbance is provided largely by nonnative mammals that have driven the extinction of insular species. The indigenous species of the sub-Antarctic islands form a unique collection of plants and animals adapted to conditions in the region. This assemblage is the result of dispersal mechanisms, community interactions and environmental conditions unique to these remote parts of the Southern Ocean. The insular indigenous species are vulnerable to the impacts of introduced mammals such as mice, rats, rabbits, feral cats, and larger herbivores such as goats, sheep and reindeer.

The response to such biodiversity threats is to develop and improve techniques to remove introduced populations from islands. With good planning, adequate techniques and sustained effort, it is possible to control or eradicate invasive species from island ecosystems through measures that are appropriate to the species and the ecosystem. Whereas control operations manage the impacts of the invasives by sustained harvesting of the invasive species populations, eradication permanently removes impacts of the invasive alien species by eliminating the entire population(s). Although eradication is preferred, raising opportunities for ecological restoration, ecosystem response to alien species removals may be unexpected and unwanted such as ecological release of invasive plants when an introduced herbivore is removed, or the irruptions of prey species after the removal of a predator. Invasive mammals are some of the easier species to eradicate, which is fortunate as they are among the most ecologically damaging. Established populations of plants and invertebrates with dormant life stages and high intrinsic rates of increase, on the other hand, present more of a challenge for eradication from islands. The feasibility of eradication will also be affected by risks to nontarget species, which may prevent the use of certain techniques and limit the use of others. Moreover, prevention of initial or further invasion is of paramount importance, especially as there is a correlation between the frequency of landfalls or visits made by humans and the number of alien species that become established. Initially such species are limited in their distribution to areas of human occupation, but most spread from the site(s) of first introduction into other areas. It is therefore important to contain and eliminate species while their distribution is limited.

Despite the adverse weather conditions and challenging topography of sub-Antarctic islands, the successful eradication of introduced species, in particular introduced mammals, from these islands is no longer a rare event. The removal of feral cats from 290 km^2 Marion Island in the south Indian ocean, the largest island where cats have been successfully eradicated (in 1991 after a $\sim$15 year campaign), was followed by (unconfirmed) success at Macquarie Island (120 km^2) in 2000. Bolstered by previous eradications of rats from small islands in lower latitudes, Campbell Island at 113 km^2 in the New Zealand sub-Antarctic represents the largest island where rat eradication was ever undertaken. Islands of the sub-Antarctic Auckland Archipelago were variously rid of mice, rabbits, goats, and cattle between 1983 and 1989, as were some small islands at Îles Kerguelen released from the effects of rabbits.

Methods used to eliminate alien invasives vary substantially depending on the target species. Biocontrol using the feline panleucopaenia (cat flu) virus (feral cats), and myxomatosis (rabbits) provided the initial knock down of the target population(s), followed by other appropriate techniques such as hunting with/without trained dogs, trapping (e.g., walk-in or leg-hold) and poisoning (e.g., 1080 and brodifacoum in artificial or natural baits, at bait stations or by bait sowing). Alien vascular plant and invertebrate species, prioritized according to the degree of threat they pose to the natural environment, especially new introductions, should be targeted immediately. Early detection, emphasis on destroying nascent foci of a potential invasion, and continually surveying for the putative eradicated species are essential. Eradication methods and their combinations (mechanical, chemical, biological) for almost all vascular plant species may amount to considerable time spent cutting or digging out mature individuals, treating stumps with biodegradable herbicides, and blanket spraying of dense infestations. Little information for eradication of both plant and invertebrate invasions in the sub-Antarctic exists, perhaps due to the difficulty of doing so once these have become established.

To achieve eradication, a well-accepted set of conditions must be met, such as proper planning, a commitment to completion of the eradiaction, putting the entire population of the target species at risk, removing them faster than they reproduce, and preventing reinvasion. In fact, prevention of reintroduction is as important as eradication itself. Every island has its own plant and animal species, and where there are several animal invasives, it is important to remove them in the correct order. The removal of one may trigger an increase in the second or make the second more difficult to find or remove. Likely changes to the ecosystem following the initial knockdown of numbers of the introduced animals should be taken into consideration. Support from the local community (expeditioners and/or inhabitants) and public at large is highly desirable, and an ability to demonstrate the benefits of the eradication programme (e.g., the recovery of threatened bird populations after elimination of an alien predator), balanced with ethical considerations (e.g., humaneness of techniques used; clearance by ethics committees) is essential. The positive values of rare breeds of feral animals are a consideration, but their continued presence on sub-Antarctic islands are conditional upon lack of impacts on the primary indigenous values, and each case must be judged on its merits.

In the context of restoration of the intrinsic values of the sub-Antarctic islands, it should be appreciated that no modified habitat can be returned to its pristine condition after alien introductions have been eliminated, but that in time it might resemble the original condition. Immediate results may be spectacular, but a long time may be required for the development of a system that resembles the original one. Indeed, the reinstatement of biotic communities in their original pristine state can seldom be seen as an achievable goal. Prevention is infinitely better than cure.

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See also **Auckland Islands; Biodiversity, Terrestrial; Campbell Islands; Diseases, Wildlife; Kerguelen Islands (Îles Kerguelen); Macquarie Island; Pollution; Tourism**

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RIISER-LARSEN, HJALMAR

Hjalmar Riiser-Larsen was born June 7, 1890, in Oslo and made his name within pioneer flying. Although he helped to start both a separate Norwegian Air Force and Norwegian civil aviation routes, he is probably best known for his expeditions with Roald Amundsen.

Riiser-Larsen began his career in the navy, but an experience as a passenger on a navy plane in 1913 turned him to flying himself. He was in the first group of naval pilots to be trained in Norway in 1915, and he quickly made a name for himself. In autumn 1919, he was in Germany testing new planes for the navy, and there he had his first experience of dirigibles. In 1921, he received training as a dirigible operator in Britain. He pioneered long-distance flying in Norway, with his friend and fellow pilot Finn Lützow-Holm.

In 1925, he was the pilot of one of the two aircraft, named *N24* and *N25*, that Roald Amundsen intended to fly to the North Pole. Due to mechanical difficulties, the party landed on the ice at 87°43′ N, and it was Riiser-Larsen's flying skills that brought all six men back to Svalbard in *N25* three weeks later. In 1926, he was navigator and pilot on the dirigible *Norge* during the Amundsen-Ellsworth-Nobile transpolar flight from Svalbard to Alaska, over the North Pole. In 1928, he joined in the search for Nobile's crashed dirigible *Italia,* and later for Amundsen's lost plane.

Riiser-Larsen was the leader of Lars Christiansen's third *Norvegia* expedition to the Antarctic in 1929–1930. With two planes, and Lützow-Holm as fellow pilot, Bouvetøya was photographed from the air, as was also the western part of Enderby Land. On December 22, 1929, Riiser-Larsen and Lützow-Holm landed their plane off a small island by Cape Ann and raised the Norwegian flag, a claim not sustained by the Norwegian government. In mid-January they met the RRS *Discovery* with the British, Australian, New Zealand Antarctic Research Expedition, led by Sir Douglas Mawson, and a friendly agreement was made on where the two expeditions should work. Riiser-Larsen went on to the discovery and aerial charting of Kronprins Olav Kyst and Kronprinsesse Märtha Kyst in what is now Dronning Maud Land.

Riiser-Larsen was again leader on the second half of the fourth and final *Norvegia* expedition, when Prinsesse Ragnhild Kyst was mapped from the air and annexed for Norway, becoming part of the Dronning Maud Land claim in 1939.

In 1933, he led his own expedition to the Antarctic, intending, with two companions and fifty-eight dogs, to explore the coastline from Enderby Land to the Weddell Sea. The expedition was unloaded on to the off-shore sea ice, which broke up during the first night. The camp was divided in two and the ice floe with the men and four dogs drifted out to sea, while the other dogs disappeared. Thanks to a shortwave radio, the men could broadcast an emergency call to the whaling fleet and they were picked up after a couple of days before the ice floe disintegrated. This was the last of Riiser-Larsen's polar expeditions, and he devoted himself thereafter to the development of aviation in Norway. He was highly decorated by several nations during his career. He died in Copenhagen on June 3, 1965.

Susan Barr

See also **Amundsen, Roald; Bouvetøya; British, Australian, New Zealand Antarctic Research Expedition (BANZARE) (1929–1931); Christensen Antarctic Expeditions (1927–1937); Christensen, Lars; Mawson, Douglas**

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RODINIA

Rodinia is the name for an ancient supercontinent (a continent that includes all of the landmasses of the Earth, surrounded by a superocean) that existed between 1000 and 750 Ma. The name Rodinia was coined by Mark McMenamin and has its origins in a Russian or Bulgarian word for "to originate" or "homeland" referring to the origins of animal life.

The concept that all of the Earth's continents had been amalgamated into a single landmass in the past was first seriously mooted by Suess in the late nineteenth century, and reiterated by Wegener in the early twentieth, finally finding general acceptance with the plate tectonic revolution of the 1960s. The first proposed Gondwana supercontinent overlapped with the age of the dinosaurs and its final amalgamation and eventual fragmentation lay fully within the period of Earth history for which we have a fossil record.

A more ancient supercontinent, existing in the period that predated the fossil record (more than 543 Ma), was first mooted in the 1970s based on palaeomagnetic evidence. However, the idea did not gain scientific acceptance until the early 1990s when a series of geological synthesis papers demonstrated a former physical connection between the continents, predating the formation of Gondwana. The name Rodinia predated the scientific acceptance of the idea by barely a year.

The modern conception of Rodinia was born out of a scientific idea called the SWEAT (Southwest US–East Antarctica) hypothesis, in which Antarctica played a key role. The acronym comes from the fact that the southwestern US and East Antarctica have sufficient geological similarities to suggest that they were linked together more than 750 Ma. This is, in particular, via distinctive fragments of an even older mountain belt, called the Grenville Belt, that had been active from 1300–1000 Ma. Fragments of the Grenville Belt were known from many continents and it quickly became apparent that they were the key to piecing together Rodinia, which had Laurentia at its core and South America on its eastern flank.

Although there are many uncertainties of timing over the exact details of the process, Rodinia appears to have formed by a series of continent–continent collisions, creating orogens (mountain belts) generally referred to as Grenvillian in the northern hemisphere, Kibaran in Africa, Albany-Fraser in Australia, and Uruaçu-Sunsás-Cariris Velhos in South America. Rodinia lasted about 200 million years, surrounded by the Mirovoi Superocean, and began to break up about 800–750 Ma. This was associated with emplacement of mafic dyke swarms (the Franklin dyke swarm is a particularly well-preserved example in Canada), formation of rift basins such as the Reelfoot rift basin which extended from the modern-day Gulf of Mexico to Illinois, and the origin of the Pacific and Iapetus (a precursor to the Atlantic) oceans. It is suggested that another supercontinent called Pannotia (residing in the southern hemisphere) briefly existed during the breakup of Rodinia.

Since its proposal, the configuration of the supercontinent has gone through much revision and, although there is scientific consensus that it existed, there is no universally agreed configuration. Following SWEAT, the AUSWUS (Australia–southwestern US) hypothesis made convincing claims for juxtaposition of the western half of Australia against the southwestern USA and similar suggestions have been made for Australia against Mexico, the AUSMEX hypothesis. Recent palaeomagnetism studies have shown that there is still considerable uncertainty in Rodinia configurations and even go so far as to argue that although Rodinia probably existed, there is no evidence for SWEAT or AUSWUS or AUSMEX.

One consequence of the conception of Rodinia is that it supported a palaeoenvironmental hypothesis called the "Snowball Earth" recently championed by Paul Hofmann. Brian Harland first proposed this as early as 1964 and the hypothesis presented the surprising implication that in the past the Earth was encased in ice from pole to equator to pole. On some Rodinia reconstructions the continents are largely distributed in the Southern Hemisphere and within 60 degrees of the equator. Unexpectedly, if sedimentary rocks from this time are examined, a strange mix of limestones that formed in warm shallow marine conditions, so-called cap carbonates, and glacial sediments are found. The glacial sediments are similar to those seen in Scotland and Canada today, sands and gravels and unsorted mixtures of mud and gravel called diamictons, but the Rodinia deposits have been converted to rock.

The distribution of these rocks supports the unexpected conclusion that there was continental glaciation from high latitudes right to the equator. The warm-water shallow-water marine limestones are found resting on top of the glacial sediment deposits in many cases and this relationship suggests that there was low altitude glaciation as well as low latitude glaciation. An explanation for this touches on one of the major current competing hypotheses for the onset of global glaciation. This invokes declining levels of atmospheric carbon dioxide, a greenhouse gas, as the major cause. Although it relates more to the death than the birth of Rodinia, a keystone of the "Snowball Earth" hypothesis is that the breakup of Rodinia resulted in increased weathering rates and carbon dioxide draw-down that began a downward spiral into global glaciation.

East Antarctica was at the heart of the first evidence for Rodinia, which came from the observation that it and the southwestern US were once side-by-side. Antarctic geological data and discoveries have subsequently been of key importance in the development of the idea, which has been extremely stimulating for geological study of the Precambrian history of the continent. The conception of Rodinia has made geologists look again at East Antarctica, which has been assumed to have been unchanged since Archaean times, and find new evidence for Proterozoic geological subdivisions of the craton and former mobility between these younger component parts.

ALAN P. M. VAUGHAN

See also **Gondwana; Plate Tectonics**

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RONNE ANTARCTIC RESEARCH EXPEDITION (1947–1948)

Led by Norwegian-American Finn Ronne (1899–1980), the Ronne Antarctic Research Expedition (RARE) of 1947–1948 was the last large private expedition to Antarctica. It explored both coasts of the Antarctic Peninsula and the Weddell Sea's southern margin, on the ground and with aircraft, and also marked the first time that women wintered in Antarctica.

Cdr Finn Ronne, USNR, served as ski expert and dog-driver on Richard E. Byrd's second Antarctic expedition and was second-in-command of East Base, at Stonington Island in Marguerite Bay on the west side of the Antarctic Peninsula, during the US Antarctic Service Expedition (USAS) of 1939–1941. His father, Martin Ronne, was a sailmaker on Roald Amundsen's Norwegian Antarctic Expedition (1910–1912) and sailmaker, ski instructor, and dog-driver on Byrd's first Antarctic expedition.

Although a private expedition, the RARE received funding from the American Geographical Society, the Office of Naval Research (which paid for scientific work), and the North American Newspaper Alliance, which bought exclusive news rights. The US government loaned clothing and equipment, including a 1200-ton diesel-powered wooden US Navy tug (renamed *Port of Beaumont*) commanded by Cdr Isaac Schlossbach USN (Ret.); three US Army Air Force ski-equipped aircraft (a Stinson L-5, a single-engine Norseman C-64, and a twin-engine Beechcraft C-45); and two US Army Weasel tracked vehicles.

The expedition sailed from Beaumont, Texas, on January 25, 1947, with forty-three huskies to be used as sledge dogs, but half died of distemper en route to Antarctica. Among the expedition's twenty-three members, nearly all unpaid volunteers, were Edith ("Jackie") Ronne, wife of the expedition leader, and Jennie Darlington, wife of pilot Harry Darlington. The women had not planned to participate in the expedition, but at a late hour Finn Ronne convinced his wife to come to write its newspaper dispatches and other records. Jennie Darlington, asked to join as well, became pregnant during the expedition and nearly gave birth to the first native Antarctican.

The expedition arrived at Stonington Island on March 12; *Port of Beaumont* was frozen into Back

Bay, 500 yards (450 m) from the base, through the winter. Plans to reuse the USAS's former East Base were complicated when Ronne found it damaged and looted. Recriminations flew, with Ronne suggesting that the eleven occupants of the UK's neighboring Falkland Islands Dependencies Survey (FIDS) Base E might have been responsible, while the FIDS members said the destruction was caused by visiting Argentines or Chileans. This led to initial chilliness in relations between the two expeditions, but they soon grew closer and eventually cooperated on field work, building on their respective strengths: dog teams and dog-handling (British) and aircraft (Americans).

The expedition's main objectives were to determine whether the mountain range running along the Antarctic Peninsula connected to either the Queen Maud Mountains or the mountains of Marie Byrd Land; and to determine whether the Weddell and Ross seas were connected, by exploring the Antarctic continent's, and the world's, last major stretch of unexplored coast, along the Weddell Sea from the Antarctic Peninsula to Coats Land. The first 3-hour reconnaissance flight to the south was made on March 18, and the expedition's scientists began collecting data on tides, weather, and seismic activity.

A six-man party set up a weather station on the 6000-foot (1830 m) peninsular plateau on July 15. After being confined to their tents for eight days by harsh weather, two men, physicist Harris-Clichy Peterson and geologist/surveyor Robert Dodson, remained at the camp while the others returned to Stonington Island. Late on July 26, Dodson appeared at the American base with the news that Peterson had fallen into a crevasse nine miles away. A joint American-British team rescued him the next day. He was not seriously harmed despite plunging 110 feet (34 m)—and remaining wedged for 10 hours lying face-down in the crevasse.

During a British-American exploration flight to the east side of the Peninsula on September 15, the two planes became separated. The British plane crash-landed on sea ice in Marguerite Bay, and only after a 9-day search by the Americans was its crew found unhurt.

An advance base for weather observation was established on September 29 at Cape Keeler on the east side of the Antarctic Peninsula plateau, along the Weddell Sea coast 125 miles (200 km) southeast of Stonington Island.

Aviation was restricted by unfavorable weather, but several notable flights—usually involving a shuttle system using two planes to relay fuel—were achieved. On November 21 and December 12, Ronne navigated flights along the southern coast of the Weddell Sea and found that it connects to Coats Land, with no outlet south to the Ross Sea. He named the newfound territory Edith Ronne Land. However, later investigations during the IGY, also by Ronne, determined that most of the area is an ice shelf, so the name Ronne Ice Shelf is applied to the area west of Berkner Island, separating it from the Filchner Ice Shelf. On November 23, a long flight was made to the southwest, over the eastern and southern coasts of Alexander Island, with a landing (the first) at Charcot Island on the return to base.

Meanwhile, surface field parties were active. Dodson and chief scientist Robert Nichols, on a geological survey using a thirteen-dog team, made a 90-day (September 28 to December 26) sledge trip south to George VI Sound, covering 450 miles (725 km). A four-man British-American Weddell Sea coast party, with three sledges and twenty-three dogs, covered 1180 miles (1900 km) in 106 days, from October 9, 1947, to January 22, 1948.

Two icebreakers taking part in the US Operation Windmill, USS *Burton Island* and USS *Edisto,* broke out *Port of Beaumont,* still held by sea ice, on February 20, 1948, and the expedition reached New York on April 15 that year.

The Ronne expedition achieved a great deal with its relatively limited budget of less than $50,000, far smaller than many expeditions of its era. It explored more than 250,000 square miles (650,000 km^2) of Antarctica, and in 346 hours of flight time, including eighty-six landings in the field, took nearly 14,000 photographs covering 450,000 square miles (1,165,000 km^2), crucially, with ground control.

JEFF RUBIN

See also **Amundsen, Roald; Byrd, Richard E.; Norwegian *(Fram)* Expedition (1910–1912); United States (Byrd) Antarctic Expedition (1928–1930); United States (Byrd) Antarctic Expedition (1933–1935)**

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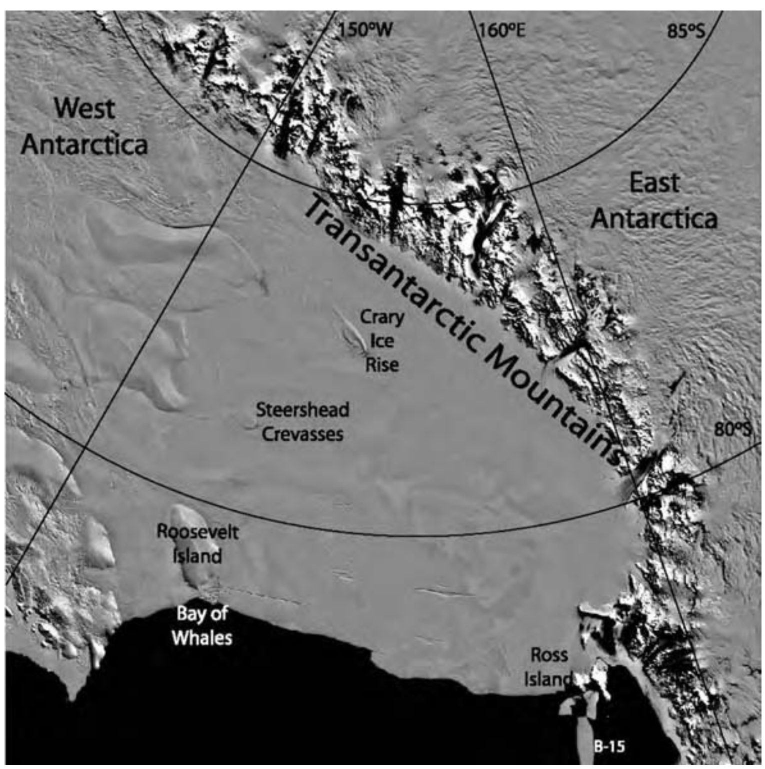
ROSS ICE SHELF

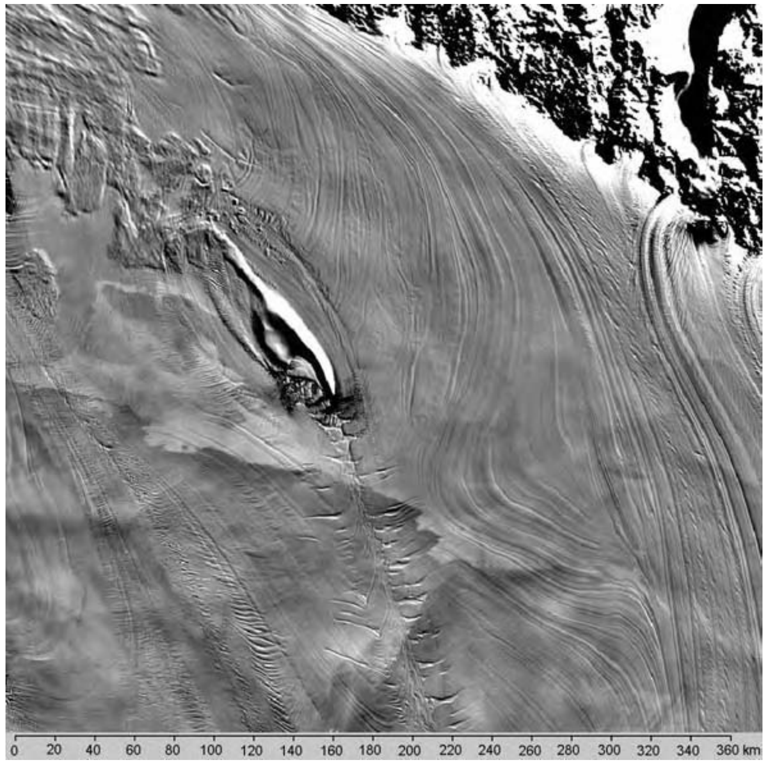
The Ross Ice Shelf is a vast, roughly triangular plate of thick floating ice extending from about 78° S to 85° S and from 150° W to 160° E. It is about 520,000 km^2 in area (roughly equivalent to Texas or Spain), making it the largest single sheet of floating ice in the world. The average depth of the ice is approximately 370 meters. McMurdo Station and Scott Base, both on Ross Island, lie near the ice shelf's northwestern corner. The Bay of Whales and Roosevelt Island, near the former exploration bases sharing the name Little America, lie near its northeastern corner. The southwestern edge is defined by 700 kilometers of the Transantarctic Mountains while the eastern edge is marked by a series of ice streams emerging from West Antarctica. Ice up to 700 meters thick flows into the ice shelf along these edges from West Antarctic ice streams and East Antarctic outlet glaciers, traveling at speeds up to 800 meters per year. These ice flows merge to form the ice shelf, along with snow which accumulates on the surface at an average rate of 15 centimeters per year (in water equivalent units). The northern edge of the shelf constitutes the calving ice front.

The ice is not stagnant, but flows generally horizontally northward driven by gravity, which causes it to thin and spread out, and by the push of the glaciers and ice streams that discharge into it. It also moves downward as additional snow accumulates on the surface. The horizontal motion is resisted by the water in which the ice shelf floats and by areas where the ice comes into contact with stationary rock, principally the Transantarctic Mountains and isolated elevated regions of the seafloor: Roosevelt Island, Crary Ice Rise, and Steershead Crevasses are three primary regions of subshelf resistance. Ice moves over or around these areas of contact, creating fields of crevasses that can fracture the ice through its full thickness. Ice at the calving front is typically 200 meters thick and moves at about 1000 meters per year.

Water circulates in the cavity between the bottom of the ice and the sea floor. The circulation pattern is driven by tidal forces and is generally counterclockwise, taking about 5 years for a full transit beneath the ice. As the circulating water is forced downward



Satellite image of the Ross Ice Shelf using data from NASA's Moderate Resolution Imaging Sensor (MODIS). South Pole is off the top of figure. (Image courtesy of National Snow and Ice Data Center.)



Satellite image detail of flowstripes on the Ross Ice Shelf. Transantarctic Mountains are in the upper right and Crary Ice Rise is the bright and dark feature left of center. Ice flow is from upper left to lower right. In the upper left is a region of grounded ice in the mouth of Whillans Ice Stream. As this ice flows around Crary Ice Rise, crevasses are formed that are carried along in the ice shelf. Evidence of time-variable flow is seen in the large looped flowstripes right of center. (Image courtesy of National Snow and Ice Data Center.)

by the increasing ice thickness, it melts the underside of the ice shelf. Conversely, as the water rises on its journey back out, it freezes to the underside. This causes the water cavity to be deeper on the western side (about 500 meters deep) and shallower (about 200 meters deep) on its eastern side.

In most years, the surface of the ice shelf receives snow and does not melt. This snow builds up, compressed by subsequent snowfalls. Ice is lost primarily by the calving of icebergs at the shelf front. These icebergs can be extremely large, as in the case of the Connecticut-sized B-15 iceberg formed in 2001. Calving is episodic and generally removes only a portion of the ice front, which is then replaced by the continued seaward flow of the shelf.

The ice front has remained at approximately the same position for the past century, with northward flow balancing the calving of icebergs from the front. At the end of the last glacial period the region of the Ross Ice Shelf contained ice so thick that the base of the ice contacted the bed nearly everywhere, and grounded ice extended an average of 200 km farther north, approaching Coulman Island. As the climate began to warm approximately 20,000 years ago, the ice sheet began to thin and retreat. As grounded ice thinned and retreated, a floating ice shelf was formed. Retreat of the shelf front began about 11,400 years ago.

Aside from regions where concentrated stresses create crevasses, the surface of the Ross Ice Shelf is very flat, rising less than 1 meter over a distance of 10 kilometers. This flatness, as well as the great southerly extent of the Ross Ice Shelf (within 550 kilometers of the South Pole), was favored by early explorers. Both Roald Amundsen and Robert Falcon Scott chose to make their treks to the South Pole across the Ross Ice Shelf.

This flatness is deceptive; precise satellite sensors have revealed an extensive set of subtle surface features that record the last millennium of ice flow into the ice shelf. The feeding glaciers and ice streams introduce sets of flowstripes that trace the path of ice flow across the ice shelf. The western third of the ice shelf shows a steady flow from East Antarctica, while the eastern third shows a similar steady pattern of flow from the northern part of West Antarctica. The middle third, however, shows distorted flowstripes indicating time-variable flow of the incoming ice streams.

Sir James Clark Ross is believed to have discovered the ice shelf in 1841. Study of the Ross Ice Shelf began with the explorers of the first decade of the twentieth century who collected the first information on surface elevation, despite the hardships of traversing the shelf's surface by dogsled and skis. Admiral Richard Byrd's expeditions of Antarctica, begun in 1928, introduced airplanes as a means to survey more of the shelf's area. The first circumnavigation of the shelf was conducted from 1957 to 1958 during the International Geophysical Year using snow tractors. This traverse party, led by Albert Crary, made the first extensive measurements of the shelf's thickness and the depth of the water cavity below using seismic techniques, used multiple pressure altimeters to measure the elevation of the ice shelf, dug snow pits to determine snow density, hardness, and average accumulation rates, and measured snow temperatures to determine mean annual air temperatures. More intensive studies using advanced geophysical techniques were employed from 1973 to 1978 during the Ross Ice Shelf Geophysical and Glaciological Survey, which included the first hole drilled through an ice shelf providing direct access to the subshelf water cavity. Field studies have continued to the present, employing ever more sophisticated instruments and methods, including an increased use of satellite data.

Robert Bindschadler

See also **Amundsen, Roald; Antarctic Ice Sheet: Definitions and Description; British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); British Antarctic (*Terra Nova*) Expedition (1910–1913); British National Antarctic (*Discovery*) Expedition (1901–1904); Byrd, Richard E.; Climate Change; CryoSat; Earth System, Antarctica as Part of; Filchner-Ronne Ice Shelf; Glaciers and Ice Streams; Ice Sheet Mass Balance; Ice Sheet Modeling; Ice Shelves; Icebergs; ICESat; International Geophysical Year; Lambert Glacier/Amery Ice Shelf; Larsen Ice Shelf; McMurdo Station; Norwegian (*Fram*) Expedition (1910–1912); Ross Island; Ross, James Clark; Scott, Robert Falcon; Thwaites and Pine Island Glacier Basins; Transantarctic Mountains, Geology of; United States (Byrd) Antarctic Expedition (1928–1930); United States (Byrd) Antarctic Expedition (1933–1935)**

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ROSS ISLAND

Ross Island is located in the Ross Sea at 77°30′ S, 168°00′ E on the east side of McMurdo Sound. It is roughly triangular in shape, approximately 43 miles from Cape Bird on the north to Cape Armitage on the south and approximately the same distance from Cape Royds on the west to Cape Crozier on the east. Ross Island is volcanic in origin. Mount Erebus, Antarctica's largest and most active volcano, rises 12,450 feet (3795 meters) from the center of the island and Mount Terror, an extinct volcano, rises, 10,600 feet (3230 meters) 20 miles (32 km) to the east of Erebus. Two other peaks are found on Ross Island: Mount Bird, rising 5800 feet (1765 meters) just south of Cape Bird, and Mount Terra Nova, rising 6990 feet (2130 meters) between Mount Erebus and Mount Terror.

Ross Island was discovered by James Clark Ross on an expedition to find the south magnetic pole. Sailing with his two ships, the *Erebus* and the *Terror,* in January 1841, he sighted a high mountain "emitting flame and smoke in great profusion," a mountain he named Erebus. As Ross continued his exploration of the area, he discovered a bay that he named McMurdo Bay (later renamed McMurdo Sound), after the senior lieutenant of the *Terror*.

Geologically, Ross Island is the result of volcanic activity that began approximately 4 Ma with the formation first of Mount Bird, then Mount Terror, and finally, Mount Erebus, which is younger than 1 million years. Mount Erebus produces an unusual volcanic rock popularly called kenyte (technically known as anorthoclase phonlite, a unique type of feldspar). The only other place in the world this igneous rock is found is in Kenya, Africa.

There are several glaciers on Ross Island, the most visited being the Erebus Glacier, which flows from the lower slope of Mount Erebus. The Erebus Glacier flows onto the sea ice to form the Erebus Glacier Tongue. Ice caves form where the Erebus Glacier Tongue extends onto the sea ice.

Recorded temperature extremes have been as low as –50°C and as high +8°C. The monthly mean temperatures ranges from –3°C in January to –28°C in August. Drifting snow can accumulate 1.5 meters per year, although the station becomes snow-free in summer. Average wind is about 5.1 meters per second; a gust of 52 meters per second was recorded in July 1968 (NSF 1997).

The sea around Ross Island is rich with marine life, an important factor for supporting the native birds and mammals. Slow-growing sea sponges feed on the diatom rich waters. Sea anemones and sea stars, brittle stars and brittle worms, all inhabit the waters around Ross Island. Many species of fish also inhabit these waters including ones that have a natural antifreeze in their bodies that allows them to survive in the extremely cold water without freezing. Krill, small shrimplike crustaceans, are also abundant in the waters around Ross Island.

Feeding on the krill and small fish in the waters off Ross Island are two of the best-known bird inhabitants of Antarctica. Ross Island is home to three Adélie penguin colonies, the largest one at Cape Cozier, another at Cape Bird, and the most southerly Adélie rookery in Antarctica at Cape Royds. Emperor penguins, the largest of the Antarctic penguins, breed in the vicinity of Ross Island and can occasionally be seen on the sea ice nearby. Skuas also breed on Ross Island, feeding on the eggs and chicks of the Adélie penguins as well as fish and anything else edible they can find.

Seals are also found around Ross Island. The most common is the Weddell seal. Weddell seals are solitary animals, preferring to lie on the sea ice when they are not hunting for fish. When hunting for food, the Weddell seal dives beneath the sea ice and can stay underwater for more than fifteen minutes, diving to depths of more than 1000 feet (304 meters). Crabeater seals are also found in the vicinity of Ross Island. The crabeater seal is more agile on land and ice than other Antarctic seals. Occasionally leopard seals are seen in the waters around Ross Island, near the fast ice edge or penguin rookeries. The leopard seal is the only seal that regularly preys on warm blooded animals, often hunting for penguins or sea birds.

The Antarctic is home to a number of whales, and the area around Ross Island is frequented by orcas, also know as killer whales, and minke whales. Orcas are often seen during the austral summer patrolling the waters near penguin rookeries as well as the ice edge. Minke whales feed on the krill abundant in these waters during the austral summer.

Human Use and Habitation

The Heroic Era

Though discovered by James Clark Ross in 1841, no humans set foot on Ross Island until 1902 when Robert Falcon Scott, in the ship *Discovery,* made his way into McMurdo Sound. As part of his *Discovery* expedition, Scott planned to explore the Ross Ice Shelf, known at that time as the Barrier. He also hoped to find a sheltered location to set up winter quarters, a location that would also provide him access to the geographic south pole. He explored the area around Cape Bird and Cape Crozier but returned to McMurdo Sound and decided to winter at Hut Point, the southwestern extremity of Ross Island. During February and March the *Discovery* hut was constructed. Because it was too hard to heat efficiently, Scott and his men did not live in the hut but used it primarily for storage.

Discovery expedition named many of the features of Ross Island. Cape Armitage was named for Scott's navigator. Observation Hill, adjacent to present day McMurdo Station was named because, at 750 feet (228 meters), it made an excellent lookout site. The point of land where they were to build their hut was Hut Point and the bay to the south of Hut Point was named Winter Quarters Bay. These names continue in use today.

The next historic expedition to Ross Island was Ernest Shackleton's *Nimrod* expedition, 1907–1909. Shackleton had hoped to base himself near the Bay of Whales, but he found the ice there too dangerous. So he headed north towards Ross Island but was only able to get as far as Cape Royds, a spot about 22 miles (37 km) north of Hut Point and Scott's *Discovery* hut. Here, in February 1908, Shackleton constructed a small hut for himself and fifteen expedition members. From this site, Shackleton and three others made it to within 97 miles (156 km) of the geographic south pole, making use of the *Discovery* hut as a shelter while laying supply depots along the planned route. In addition to reaching the furthest point south yet achieved, Shackleton's *Nimrod* expedition made the first ascent of Mount Erebus and reached the south magnetic pole.

Scott's second (and last) expedition left England in June 1910 on the *Terra Nova.* He reached Ross Island in the first week of January 1911, but was unable to base at Hut Point because of ice conditions. Instead he chose a location about 15 miles (24 km) to the north, which he named Cape Evans in honor of his second in command. Scott constructed a new hut at Cape Evans, 24 feet wide (7.3 meters) and 48 feet long

(14.6 meters) to accommodate twenty-five men. From the hut at Cape Evans, Scott sent out two parties, one to carry out geological exploration and the other to lay a supply depot for the planned journey to the Pole. Both parties used the *Discovery* hut for shelter, and in November 1911, Scott and four companions used it as their starting point for their trek to the South Pole. Today the hut at Cape Evans remains much as it was left, slabs of seal blubber in the outer porch area and provisions and photographic supplies still on the shelves.

The final expedition to Ross Island in this time period (commonly known as the Heroic Era) was part of Shackleton's *Endurance* expedition. With the South Pole having already been reached, Shackleton concluded that the one remaining Antarctic challenge was to cross the continent from sea to sea. The route he chose was from the Weddell Sea to McMurdo Sound. The task of laying supply depots from Ross Island to the foot of the Beardmore Glacier, which Shackleton planned to traverse after reaching the Pole, was given to the captain and crew of the *Aurora*. They frequently used the *Discovery* hut as a base of operations for laying supply depots though the depots were never used. While the *Aurora* handled the McMurdo Sound end of the attempt to cross the continent, Shackleton sailed the *Endurance* to the Weddell Sea. There the *Endurance* became trapped by ice, drifted for ten months, and was eventually crushed.

The Modern Era

McMurdo Station, located on the bare volcanic rock of Hut Point Peninsula, is the largest research station in Antarctica and the logistics hub of the US Antarctic Program (USAP). The station was established in December 1955 to support research for the International Geophysical Year (IGY). Since then it has grown from a few buildings to a complex logistics staging facility of more than 100 structures. It has a helicopter pad and an outlying airport, Williams Field, as well as a landing strip on the Ross Ice Shelf, Pegasus site, and a landing strip closer in to the station on the annual sea ice. McMurdo Station is also the world's most southern seaport, with an ice pier and vessel offloading facilities located at Winter Quarters Bay.

The station has administrative facilities, dormitories, equipment repair facilities, a power plant and associated fuel storage tanks, a firehouse, a reverse osmosis water plant, and a wastewater treatment plant. Buildings are linked by above-ground water, sewer, telephone and power lines. Peak population during the austral summer can exceed 1100, with a winter population of about 250. The winter population is normally isolated from late February, when airfield operations cease, until late August.

The USAP employs Hercules (LC-130 and C-130), Starlifter (C-141), and Galaxy (C-5) aircraft in airlift operations. During the summer months, October to February, these planes fly between Christchurch, New Zealand, and McMurdo, carrying passengers and cargo. The ski-equipped LC-130s are also used for flights to South Pole Station. Twin Otters are used primarily to support more remote field camps.

Scott Base, the New Zealand research station, is situated on Pram Point at the end of Hut Point Peninsula. Scott Base was originally constructed to support New Zealand's contribution to the IGY project and as headquarters for Sir Edmund Hillary's activities in support of the British Commonwealth Trans-Antarctic Expedition, which made the first land crossing of the Antarctic continent.

Today the base has accommodations for up to eighty-six people and comprises eight main interconnected buildings that house administration areas, equipment workshops, a power plant, and a laboratory. The base also has bulk fuel storage tanks, two helicopter pads, a reverse osmosis water treatment plant and a wastewater treatment facility. Scott Base is run by the New Zealand Antarctic Institute, operating as Antarctica New Zealand. New Zealand shares use of the McMurdo airfield facilities with the US Antarctic Program.

Specially Protected Areas

Under the Antarctic Treaty System, the concept of setting aside areas for special protection was introduced by the Agreed Measures for the Conservation of Antarctic Fauna and Flora (1964). Protected areas were designated for scientific reasons. The Protocol on Environmental Protection to the Antarctic Treaty, which entered into force in 1998, provided for modifications to protected area designations, expanding on the reasons for protection to include historic, aesthetic and wilderness values as well as scientific values. A new designation was given for areas to be set aside and entered only under permit, Antarctic Specially Protected Areas (ASPAs).

Because of its unique place in the history of Antarctic exploration as well as its wealth of unusual biota, Ross Island has a number of areas set aside as ASPAs. Five sites have been designated as specially protected for their scientific values:

- ASPA No. 116, "New College Valley," Caughley Beach, Cape Bird, located at 77°13′ S, 166°29′ E, was originally designated as two sites. The two sites were merged under a single designation in 2000. Caughley Beach lies between the Cape Bird northern and middle penguin rookeries, about 1 km north of Cape Bird. The site was designated to protect one of the most extensive stands of moss, algae, and lichens in southern Victoria Land as well as the terrestrial ecosystem within the site that is the subject of continuing long-term research.
- ASPA No. 121, Cape Royds, located at 77°33′ S, 166°08′ E, is an area designated to protect the most southerly Adélie penguin colony known. The area extends 500 m offshore from the high water mark and extends inland to include the entire penguin colony and past Pony Lake (named by Shackleton's British Antarctic Expedition of 1907–1909 because they had their ponies tethered nearby).
- ASPA No. 122, Arrival Heights, Hut Point Peninsula, at 77°49′ S, 166°39′ E, is an area close to McMurdo Station designated as an electromagnetically quiet site for installation of sensitive instruments used to record data associated with upper atmosphere research programs.
- ASPA No. 124, Cape Crozier, is defined by lines joining 77°28′ S, 169°20′ E; 77°28′ S, 169°28′ E; 77°31′ S, 169°28′ E; and 77°31′ S, 169°20′ E. It was designated to protect the long-term research value of the emperor and Adélie penguin colonies found in the site that have been the subject of study for over 30 years.
- ASPA No. 130, Tramway Ridge, Mount Erebus, at 77°31′ S, 167°07′ E, encompasses the entire warm ground area of lower Tramway Ridge. It is designated to protect one of only three known high-altitude areas in the Antarctic of fumarolic activity (a volcanic area from which hot smoke and gases escape) and associated vegetation.

Historic Sites and Monuments on Ross Island

Site Number and Name	Description
HSM 15 Hut at Cape Royds	Hut built in February 1908 by the British Antarctic Expedition, 1907–1909, led by Sir Ernest Shackleton. Located within ASPA No. 157.
HSM 16 Hut at Cape Evans	Hut built in January 1911 by the British Antarctic Expedition, 1910–1913, led by Captain Robert F. Scott. Located within ASPA No. 155.
HSM 17 Cross at Cape Evans	Cross on Windvane Hill erected by Ross Sea party of the Imperial Trans-Antarctic Expedition, 1914–1916, led by Sir Ernest Shackleton, in memory of three members of the party who died. Located within ASPA No. 155.
HSM 18 Hut at Hut Point	Hut built in February 1902 by the British Antarctic Expedition, 1901–1904, led by Captain Robert F. Scott. Designated as ASPA No. 158.
HSM 19 Cross at Hut Point	Cross erected in February 1904 by the British Antarctic Expedition, 1901–1904, in memory of George Vince, a member of the expedition, who died in the vicinity.
HSM 20 Cross on Observation Hill	Cross erected in January 1913 by the British Antarctic Expedition of 1910–1913 in memory of Captain Robert F. Scott's party which perished on the return journey from the South Pole in March 1912.
HSM 21 Hut at Cape Crozier	Remains of a stone hut constructed in July 1911 by Dr. Edward Wilson's party of the British Antarctic Expedition, 1910–1913, during the winter journey to collect emperor penguin eggs. Located within ASPA No. 124.
HSM 54 Bust on Ross Island	Bronze bust on black marble erected in 1965 at McMurdo Station to commemorate the polar achievements of Admiral Richard E. Byrd.
HSM 69 Message post at Cape Crozier	Erected on January 22, 1902 by Captain Robert F. Scott's Discovery Expedition of 1901–1904. It was to provide information for the expedition's relief ships, and held a metal message cylinder which has since been removed. Located within ASPA No. 124.
HSM 73 Memorial Cross, Lewis Bay	Stainless-steel cross erected in January 1987 on a rocky promontory 3 km SE from the crash site, in memory of the people who lost their lives when their aircraft crashed into the lower slopes of Mount Erebus.
HSM 75 "A Hut," Pram Point	The "A Hut" of Scott Base, erected in 1956, is the only existing 1956–1957 Trans-Antarctic Expedition building in Antarctica. It was also the first New Zealand building erected in Antarctica.

Four ASPAs have been designated for their historic values and to provide further protection of the artifacts on site.

- ASPA No. 155, Cape Evans, at 77°38′ S, 166°24′ E, is centered on Scott's *Terra Nova* hut. Designated to protect historic structures and relics pertaining to the Heroic Age of Antarctic exploration, the site has considerable historical, cultural, and scientific significance.
- ASPA No. 156, Lewis Bay, Mount Erebus, comprises an area of approximately 15.2 km^2 at 167°28′ E, 77°25′ S. Originally designated a tomb in 1981, the site encompasses the crash zone of an Air New Zealand DC-10 aircraft that crashed into the northern slope of Mount Erebus on November 28, 1979. All 257 people on board the aircraft lost their lives in the tragedy.
- ASPA No. 157, Backdoor Bay, Cape Royds, is located at 77°33′ 10.7″ S, 166°10′ 6.5″ E. It is centered on the hut built in 1908 by Shackleton's *Nimrod* Expedition. The site was designated to provide protection for the hut and associated historic artifacts.
- ASPA No. 158, Hut Point, at 77°50′ 50″ S, 166°38′ E, consists solely of the hut built by Scott's *Discovery* expedition in 1902.

Historic Sites and Monuments

The Antarctic Treaty also provides for designating specific Historic Sites and Monuments (HSMs), a designation intended to preserve and protect individual historic sites and monuments in Antarctica. Because of its historical significance, Ross Island has eleven sites that are designated as HSMs.

JOYCE A. JATKO

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ROSS, JAMES CLARK

James Clark Ross participated in a total of nine polar expeditions, more than any other nineteenth-century naval officer, and wintered in the Arctic for a total of nine winters. Third son of George and Christian Ross, he was born at Finsbury Park, London, on April 15, 1800. Entering the Royal Navy as a first-class volunteer on April 5, 1812, he joined HMS *Briseis,* commanded by his uncle, John Ross. For seven years thereafter he served exclusively on his uncle's ships in the Baltic Sea, the White Sea, and the English Channel. In 1818, he sailed to the Arctic for the first time, as midshipman on board HMS *Isabella* on John Ross's expedition to Baffin Bay, in search of the Northwest Passage. On this voyage James Clark Ross was assigned to assist Colonel Edward Sabine with his studies of terrestrial magnetism, recording his observations. This would determine the direction of his future career.

In 1819, Captain William Edward Parry selected Ross, in part due to his expertise in magnetism and scientific investigations, to serve as midshipman on board his ship HMS *Hecla* on Parry's first Arctic expedition. Thus James Clark Ross experienced his first Arctic wintering at Winter Harbour, Melville Island, 1819–1820. In 1821–1823, he again joined Parry, as midshipman on board HMS *Fury,* wintering first at Winter Island, then at Igloolik in Foxe Basin. Ross acted as the expedition's naturalist, collecting birds, mammals, and plants. On December 26, 1822, Ross was made lieutenant and soon after his return to England was elected a Fellow of the Linnaean Society. In the following year he was bound for the Arctic once again, as second lieutenant on board HMS *Fury* on Parry's third expedition. Blocked by ice in Prince Regent Inlet, the expedition wintered at Port Bowen on the Baffin Island shore. In 1825, *Fury* was driven ashore by the ice at Fury Beach on the east coast of Somerset Island and had to be abandoned. This was a clear demonstration to Ross of the power of sea ice.

Ross's fifth expedition took him to Svalbard in 1827, second-in-command of Parry's expedition on board HMS *Hecla,* the aim of which was to reach the North Pole. Parry found a safe anchorage in Treurenburg Bay (now Sorgfjorden) in northeastern Spitsbergen, and a party led by Parry and Ross started north across the ice with boats mounted on runners. Realizing that the southerly drift of the pack ice was exceeding their northerly rate of progress, Parry finally turned back after more than a month on this "Arctic treadmill." After their return home Ross was promoted commander on November 8, 1827.

Two years later James Clark's uncle, John, invited him to be second-in-command of his private expedition, on board *Victory,* still in search of the Northwest Passage, via Prince Regent Inlet. The younger Ross made the most important sledging trips of the expedition from the ship's winter quarters at the east end of the Isthmus of Boothia. In the spring of 1831, he located the North Magnetic Pole near Cape Adelaide on the west coast of Boothia Peninsula. Later (in 1832 and 1833), he played a crucial role in the retreat north to Fury Beach and beyond, after *Victory* had been abandoned when the ice did not break up. Thus, along with the rest of *Victory*'s complement he survived four consecutive unsupported winters in the Arctic.

Ross was promoted post captain on October 28, 1834. Then, in 1836, he mounted a rescue expedition for eleven whaling ships beset in the ice of Davis Strait. In HMS *Cove* he searched Davis Strait and the Labrador Sea from mid-April until early August; the whalers (except one that was crushed by the ice) managed to get free on their own.

In September 1839, the Lords of the Admiralty chose Ross, as the Royal Navy's most experienced ice-navigator and an expert on magnetism, to lead an expedition to the Antarctic to explore that continent and to locate the South Magnetic Pole. The expedition sailed from the Thames in HMS *Erebus* and *Terror* on September 25, 1839. In the summer of 1840–1841, Ross pushed through the pack ice into the open waters of the Ross Sea and was the first to see the ice cliffs of the Great Ice Barrier or Ross Ice Shelf. Ross determined that the South Magnetic Pole lay some distance inland in Victoria Land, west of the Ross Sea. In the following summer, he returned to the Ross Sea again, and mapped more of the Barrier. In March 1842, his two ships collided in a gale and came within an ace of being driven against an iceberg. And finally in the summer of 1842–1843, he penetrated into the northwest corner of the Weddell Sea and discovered and mapped Erebus and Terror Gulf and many of the surrounding islands.

On the expedition's return to England in September 1843, Ross was knighted and was awarded an honorary degree by Oxford Univesity. On October 18 of that year, he married his fiancée, Anne Coulman, and they settled on their estate near Aylesbury.

After Sir John Franklin's expedition disappeared into the Arctic in 1845 and had not been heard of by the spring of 1847, Lady Franklin asked Ross to lead a search expedition. He sailed for the Arctic in HMS *Enterprise* and *Investigator* in May 1848. The expedition entered Lancaster Sound but, unable to penetrate further due to ice, was forced to winter at Port Leopold at the northeastern tip of Somerset Island. In the spring of 1849, sledging parties searched most of the coasts of Somerset Island. The ships were released on August 29, 1849, but again became beset in the pack and drifted helplessly eastwards down Lancaster Sound for more than 250 miles before finally being freed.

Ross's health, already affected by his long years in the polar regions, was undermined further by this, his ninth wintering, and he now retired to his estate, although he continued to be consulted by the Admiralty concerning the search for Franklin. He was made rear admiral in 1856 and died at his home on April 3, 1862.

William Barr

See also **British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); Kerguelen Islands (Îles Kerguelen); Ross Sea; Victoria Land, Geology of**

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ROSS SEA, OCEANOGRAPHY OF

The Ross Sea is typically taken to comprise the large southward embayment lying between Cape Adare on the west and Cape Colbeck on the east, discovered by

James Clark Ross in 1841. Most of that embayment is a broad continental shelf, with average depths in excess of 500 m, half of it covered by the ~500,000 km^2 Ross Ice Shelf. For many authors, however, the Ross Sea includes similarly large portions of the adjacent deeper ocean, extending eastward with the Ross Gyre and northward to at least the winter ice edge. Between the continental shelf break, near 600 m, and the northern edge of the Ross Ice Shelf, the sea floor is characterized by a series of banks and troughs that run generally north–south in the eastern sector and more northeast–southwest in the west, where several islands and seamounts appear. The largest island, also named for Ross, separates the northwest end of the ice shelf from McMurdo Sound. Roosevelt Island, directly south of the Bay of Whales, is submerged beneath the northeast extremity of the ice shelf. The bottom troughs deepen southward, with depths >1500 m north of and beneath the ice shelf, providing reservoirs for the salty, dense waters that result from sea ice formation.

While the Ross Sea continental shelf is ice covered for most of the year, the region between the shelf break and ice shelf front is usually accessible by ship during summer. This has historically facilitated expeditionary work toward the continental interior in this sector. Reduced ice concentrations first appear along the western front of the Ross Ice Shelf in late spring, becoming a large open area characterized by high biological productivity by December. By late January, this northward ice removal often meets southward ice decay from the north, opening a passage west of the dateline. After a February minimum extent, the sea ice starts to increase again from south to the north, covering the shelf region by late March or early April and reaching a winter maximum in September. As in other areas around Antarctica, sea ice extent variability reflects forcing over a larger region. Both summer minima and winter maxima in ice extent display a periodicity of several years, with a tendency for increased (decreased) sea-ice extent to be associated with a higher (lower) frequency of ENSO-scale events. Insufficient information is available to know whether ice extent and thickness have varied significantly over the last several decades.

In some areas, particularly in and north of McMurdo Sound, the sea ice is anchored fast to the shore, even during summer. Elsewhere the pack ice is free to move, and is typically advected, often at great speed, under the influence of winds, tides, and ocean currents. Studies based on GPS buoys deployed on the ice, and beset ships, have displayed rapid north-northwestward drifts up to 15 km per day. Ice can increase in thickness both dynamically and thermodynamically, with its growth and areal expansion initially dominated by frazil ice and pancake development. The rate of congelation ice growth at the base of ice floes is dependent on the difference between ocean and air temperature. More ice is produced in the southern Ross Sea where that thermal gradient is larger and prevailing winds move young ice away from the coastline.

Large and persistent areas of open water and thin ice (polynyas) are a common feature of the Ross Sea, and play an important role in many physical and biogeochemical processes, including heat transfer between ocean and atmosphere, and in phytoplankton production. The large Ross Sea Polynya results mainly from southerly winds flowing off the Ross Ice Shelf east of Ross Island, in turn fed by katabatic (gravity drainage) flows down valleys along the Transantarctic Mountains. It is also influenced by cyclogenesis events in the eastern Ross Sea. The smaller Terra Nova Bay Polynya occupies a coastal area of ~6000 km^2 on the western side of the Ross Sea, and is maintained by katabatic winds from interior East Antarctica that flow down the Reeves Glacier. These winds push newly formed ice away from shore, while the Drygalski Ice Tongue prevents pack ice from drifting northward and filling the Polynya, which plays a key role in the thermohaline circulation of the Ross Sea.

Summer waters on the Ross Sea continental shelf are among the best sampled around Antarctica due to the generally ice-free conditions and presence of ship-supported research stations. However, winter data are scarce, as are measurements from underneath the Ross Ice Shelf. Physical features of the water column, particularly in the western Ross, are strongly influenced by the persistent polynyas, beneath which High Salinity Shelf Water (HSSW) is generated by near-continuous freezing during autumn and winter. The densest water mass in the Southern Ocean, HSSW has temperatures close to the sea surface freezing point, ~–1.9°C, and salinities above 34.75 ‰, increasing with depth. Stronger surface forcing on the western shelf produces positive east–west salinity and density gradients, with the saltiest water near-bottom spreading both north and south. HSSW that reaches the continental shelf break can mix with Circumpolar Deep Water (CDW) to form new Antarctic Bottom Water. HSSW that moves southward can flow beneath the ice shelf, where it interacts with the ice, becoming colder, but also fresher and lighter in the process, emerging as Ice Shelf Water (ISW). Colder than the sea surface freezing point, ISW flows northward at intermediate depths (300–600 m), also mixing with CDW near the shelf break and contributing to bottom water formation.

Low Salinity Shelf Water (LSSW) is found at intermediate depths and below in the central-eastern

Ross Sea, and probably forms mainly at the sea surface during winter. Antarctic Surface Water (AASW) occurs throughout the continental shelf region in summer and over the deep ocean year round. It derives in part from the upwelled and modified CDW, and is characterized by higher temperatures, lower salinities, and a shallow mixed layer during summer. The surface mixed layer is relatively stable and contains meteoric and other material released by melting ice, favoring the onset of intense phytoplankton blooms. Recent freshening of Ross Sea waters may result from increased precipitation, reduced sea-ice production, and increased melting of glacial ice, but much of the observed change is believed to be imported from coastal regions to the east.

Surface circulation in the Ross Sea is dominated by the winds, while at greater depths the flows are strongly influenced by the submarine ridges and troughs. Time series current measurements have now been made at numerous locations over the shelf and slope. In combination with mathematical models, these measurements show the circulation to be highly variable in space and time. The circulation has a small vertical shear below the mixed layer and is strongly affected by bottom topography due to the weak stratification. Our understanding of the circulation and transformation of waters in the cavity beneath the Ross Ice Shelf also relies largely on modeling efforts. A relatively sluggish circulation under the ice shelf contrasts with stronger flows close to the ice front. Chlorofluorocarbon (CFC) measurements in water masses that have circulated beneath the ice shelf indicate that HSSW can evolve to ISW can in as little as 3–4 years.

A strong frontal region, the Antarctic Slope Front, separates shelf waters from the deeper ocean along the continental shelf break. This feature is topographically controlled and constitutes an important area for the vertical and lateral exchange of heat, salt, freshwater, nutrients, particulates, and atmospheric gases. While largely subsurface, the Antarctic Slope Front has also been related to high biological productivity. Temperature is the best indicator of this front, often showing horizontal gradients of 2–3°C in $<$20 km. Tides in the Ross Sea are predominantly diurnal (i.e., one maximum and minimum occur daily), with velocities on the central continental shelf typically about 10–20 cm s^{-1}. Tidal heights can exceed 0.8 m under the eastern Ross Ice Shelf, less than beneath the Filchner and Ronne Ice Shelves in the southern Weddell Sea. Under the ice shelves, tides are expected to provide most of the kinetic energy for ocean mixing and ablation of the basal ice. Tidal currents are largest along the shelf break, again with the diurnal constituents being dominant, with measured current speeds sometimes exceeding 100 cm s^{-1} during spring tide. These currents can strongly modify the location of the Antarctic Slope Front and play a major role in the mixing of the various water masses that come together there, and in the on cross-slope drainage of dense waters into the deep ocean.

The fauna of the Ross Sea ecosystem are typical of other Antarctic regions and depend on phytoplankton—a primary food source for shrimplike krill, which in turn are consumed by fish, seals, whales, and penguins. Some studies suggest that the amount of phytoplankton in the Ross Sea can be twenty times that in the ocean off Bermuda during the summer. The production of zooplankton (secondary producers), however, is like that found in other coastal regions of the Southern Ocean, and is dominated by two similar and probably competing krill species: *Euphausia superba* and *Euphausia crystallorophias*. Winds and mesoscale cyclones influence the spatial and temporal distribution of sea ice, as well as the upper ocean mixed-layer depth, thereby controlling primary production in the ice and open water systems. The Ross Sea area is particularly fertile because winds clear away the sea ice, creating a large spring polynya in the southwest sector in November and December. Exposure of surface waters to sunlight allows phytoplankton to flourish, to the extent that chlorophyll concentrations typically exceed 5 mg m^{-3} over an area of about 100,000 km^2, vs. < 0.05 mg m^{-3} in low productivity central ocean gyres. In the cold, dark, and diverse benthic (close to the sea floor) environments, many animals grow slowly, but are long-lived and sometimes reach giant size.

The Ross Sea fishery is the southernmost in the world, with Antarctic toothfish currently constituting more than 95% of the catch, which has steadily increased from about 40 tons in 1998 to over 1800 tons in 2003. In early 2003, New Zealand fishermen working this sector captured the first live specimen of *Mesonychoteuthis hamiltoni,* a deep-sea squid. Almost 20 feet (6 meters) long, half the apparent full-grown size, with spiked tentacles and huge, protruding eyes, the monster was feeding on Patagonian toothfish caught on a longline. About eighty species of local fish include four families and fifty-three species of the endemic perciform suborder Notothenioidei. Mainly a benthic group, notothenioids have adaptively radiated to pelagic and semipelagic realms, dominating the fish fauna of the southern Ross and playing a key role in the food web. Of the four notothenioid families, nototheniids show the most ecological and dietary diversification, with pelagic, cryopelagic, epibenthic, and benthic species. *Pleuragramma antarcticum* constitutes $>$90% of both the abundance and biomass of the midwater fish fauna. Antarctic petrels, south polar skuas, emperor and Adélie penguins, Weddell seals, and minke and killer whales are the higher vertebrate components of the food web, and all prey on notothenioids in some measure.

The Ross Sea supports large populations of upper-trophic level organisms, with 25% and 30% of the world populations of the circumpolar emperor *(Aptenodytes Forsteri)* and Adélie penguins *(Pygoscelis Adeliae)* nesting along its coastline, which represents less than 10% of the Antarctic continental margin. There are thirty-eight Adélie penguin rookeries in the Ross Sea, with more than 1 million breeding pairs. The distribution of Adélie colonies is controlled by the location of polynyas, which allow access to breeding sites and also provide food early in the spring when the sea is still frozen. Adélie penguin colonies in the Ross Sea region have displayed significant variation in size from year to year, changes that are believed to be closely related to sea-ice extent. Because Adélie populations were smaller during the late 1950s to early 1970s, ice extent in the Ross Sea could have been greater at that time.

GIORGIO BUDILLON

See also **Adélie Penguin; Antarctic Surface Water; Benthic Communities in the Southern Ocean; British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); Circumpolar Deep Water; Emperor Penguin; Fish: Overview; Food Web, Marine; Gigantism; Ice Shelves; Marine Trophic Level Interactions; Pack Ice and Fast Ice; Phytoplankton; Polar Lows and Mesoscale Weather Systems; Polynyas and Leads in the Southern Ocean; Ross Ice Shelf; Ross Island; Ross, James Clark; Sea Ice: Types and Formation; Southern Ocean: Fronts and Frontal Zones; Squid; Tides and Waves; Weddell, Ross, and Other Polar Gyres; Zooplankton and Krill**

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ROSS SEA PARTY, IMPERIAL TRANS-ANTARCTIC EXPEDITION (1914–1917)

On September 18, 1914, Sir Ernest Shackleton said farewell to eleven members of the Ross Sea Party led by Lieutenant Æneas Mackintosh, their task to depot supplies on the Great Ice Barrier (now known as the Ross Ice Shelf) between Ross Island and the Beardmore Glacier, for Shackleton's proposed crossing of Antarctica from the Weddell Sea to McMurdo Sound.

Shackleton's Imperial Trans-Antarctic Expedition was supported by government and private funding amounting to approximately £60,000, although the Ross Sea part of the plan was considerably undercapitalized. Its members included three Antarctic veterans, Mackintosh, Ernest Joyce, and James Paton, and the expedition had 80 tons of stores, nearly thirty dogs, and a Girling motor sledge. In Sydney, Australia, the ship *Aurora,* last used for Douglas Mawson's Australasian Antarctic Expedition, was refitted, and late appointments were made, including of scientists and crew. Mackintosh was still endeavoring to raise funds right up until the expedition finally left Hobart on December 24. After visiting Macquarie Island, *Aurora* reached Cape Evans in McMurdo Sound on January 16, 1915.

Four sledging parties of three men each planned to depot supplies at 80°S before the onset of winter. However, the motor sledge broke down, and, with loads exceeding 1000 pounds (450 kg), the men were forced to relay on difficult surfaces with low temperatures. It was tough on the men but most affected the dogs, many of which had started unfit and subsequently died. On February 11, 1915, the Bluff depot was placed at 79°52′ S, and the same day, on the far side of the continent, Shackleton's ship *Endurance* reached its southernmost point in the Weddell Sea.

The return journey from 80°S began on February 24, and on March 6, six men who had returned to Hut Point were collected by *Aurora*. The others arrived at Hut Point a month later, and then had to wait until the reforming of the ice permitted their 15-mile (24 km) journey to Cape Evans, where the party had settled into the hut built for Scott last expedition.

There were now ten men ashore; Mackintosh, Joyce, Ernest Wild, Alexander Stevens (chief scientist), Dick Richards, Keith Jack, Rev. Arnold Spencer-Smith, John Cope, Victor Hayward, and Irvine Gaze. Meanwhile, while Mackintosh, the ship's captain as well as leading the party on land, was ashore with the sledging party, First Officer Joseph Stenhouse was responsible for the task of locating a suitable winter mooring. Cape Evans was selected.

The ship was thought to be secure for the winter, but on May 6 a blizzard broke up the ice in McMurdo Sound. Leaving two anchors on the beach, *Aurora,* still loaded with stores, drifted helplessly into the Ross Sea. Frequent attempts were made with wireless to contact Cape Evans, but, in late July, ice pressure put such a strain on the ship that the rudder was smashed, the vessel threatened to disintegrate, and preparations were made to abandon ship. In a blizzard the mizzen mast and aerials were damaged; further problems included petty thieving and the near death of Stenhouse from carbon monoxide poisoning.

Those at Cape Evans assumed the ship was lost, and there was also concern for those sledging, but eventually the shore party was reunited on June 2. Plans were then made for the next season, stores were tallied, equipment was serviced, and clothing and footwear were made by Joyce. Sledging began on September 1, before spring was properly started, when stores were taken to Hut Point. The motor sledge was returned to Cape Evans but not used agaom. There were now only four fit dogs and, leaving geologist Stevens behind, the others set out on October 1. The intention was to move further supplies to the Bluff depot and from there to the Beardmore Glacier, a distance of 330 miles (530 km). Meanwhile, in the next month, *Endurance,* her hull crushed, sank in the Weddell Sea.

After a few weeks sledging, a second Primus stove failed and it was decided to send Cope (the supposed medic, although he had little true training), Gaze, and Jack back to base. The others in two parties led by Mackintosh and Joyce, reached 82° S on January 16, 1916. By then Mackintosh and Spencer-Smith were ill and on January 22 Spencer-Smith was left in a tent while Mackintosh, Joyce, Wild, Richards, and Hayward continued south. On the evening of January 26, Joyce, Wild, and Hayward placed the final depot in "The Gap" near Mount Hope. Spencer-Smith was then collected and placed on a sledge, and the party continued homeward until February 17, when a blizzard set in for five days. With the party low in food and fuel, Wild was left to care for Mackintosh and Spencer-Smith, while Joyce, Richards, and Hayward made a dash for the Bluff depot. They collected supplies and returned six days later.

Winter was approaching and all of the men were suffering from scurvy, particularly Spencer-Smith, Mackintosh, and Hayward. On March 7, after leaving Mackintosh with a week's provisions, the others headed for Hut Point to try to get Spencer-Smith back to safety; the next day, however, Spencer-Smith died. Leaving Hayward at Hut Point, Joyce, Wild, and Richards returned for Mackintosh who had been alone for five days. Shackleton's needs had been met, but at a high price.

As the five men recovered, Mackintosh decided on May 8 to cross with Hayward to Cape Evans against the advice of the others. The two men left on their own and were never seen again. Within hours a blizzard broke up the new ice, and it was not until July 15 that Joyce, Wild, Richards, and the four dogs made the crossing. With the party of seven reunited at Cape Evans, the men concentrated on sealing and on making scientific observations. In September, however, Richards took ill with heart trouble, although Cope, who had previously spent days in his bunk, nursed him back to health. In the spring, trips were made to Cape Royds for penguin eggs, and in December a visit was made to Spencer-Smith's grave, where a cross was erected. Later a further cross was placed on Wind Vane Hill.

Meanwhile, *Aurora* broke free on February 12, 1916, and on March 15 they left the pack ice. Two weeks later, using a jury rudder constructed by carpenter Clarence Mauger, and receiving a tow from the tug *Dunedin, Aurora* arrived at Port Chalmers. By late April the expedition was in effect bankrupt, and, within a month, the British, Australian, and New Zealand governments were planning the relief of the men on Ross Island and repairs were begun on the ship. In October Captain John King Davis was appointed to lead the relief expedition, and Stenhouse and three of his crew were dismissed. Shackleton, having arrived at South Georgia and subsequently rescued the men of *Endurance,* had turned his attention to the Ross Sea Party. He immediately sailed for New Zealand, reaching Wellington on December 2, and on December 20 he sailed as a passenger on the relief expedition, the governments having refused to let him have any official position of authority.

On January 10, 1917, Richards slowly regaining his health, was looking for seals when he saw *Aurora*. The men quickly packed a sledge and headed towards the ship, where, to their astonishment, they were met by Shackleton. Further searches were made for Mackintosh and Hayward before *Aurora* again headed north. On the evening of February 9, they reached Wellington, where a civic reception was given. *Aurora* was returned to Shackleton and sold, and the expedition paid off. Later, with Paton again aboard serving as bosun, Aurora was lost with all hands while making a passage between Australia and South America.

David Harrowfield

See also **Australasian Antarctic Expedition (1911–1914); British Antarctic *(Nimrod)* Expedition (1907–1909); British Antarctic *(Terra Nova)* Expedition (1910–1913); British National Antarctic *(Discovery)* Expedition (1901–1904); Davis, John King; Imperial Trans-Antarctic Expedition (1914–1917); Ross Ice Shelf; Ross Island; Shackleton, Ernest**

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ROSS SEAL

The Ross seal, *Ommatophoca rossii,* is a member of the carnivore family Phocidae (true or earless seals) and one of four distinct Antarctic phocid seals. It has a circumpolar distribution around Antarctica. The Antarctic seals colonized then temperate Antarctic seas about 15 Ma, and subsequent cooling and eventual glaciation of the Antarctic led to speciation among the ancestral phocid seals. The oldest evidence of the Ross seal is a fossil mandible from New Zealand, which dates from the late Pliocene.

The name "Ross seal" derives from James Clark Ross, who collected two of these seals in 1840 during his voyage of exploration into the Ross Sea on the HMS *Erebus*. The genus name is from the Greek *omma* meaning eye, highlighting its obviously large eyes. This is possibly an adaptation for pursuing prey under the ice and at depth.

Ross seals grow from 2 m to 2.6 m long and up to 225 kg. Females are slightly larger than males. The pelage is the shortest of any pinniped. It is dark brown dorsally and cream or tan coloured ventrally, with several dark stripes radiating down the throat from the mouth and some spotting along the boundary between the countershaded dorsal-ventral pattern. Compared with other Antarctc phocids, Ross seals have relatively small but robust bodies with short, broad heads that can be withdrawn into rolls of fat about the neck. The short snout gives a blunt pointed profile. The eyes are noticeably large and forward pointing and the ear openings are very small. The front teeth are all small, with the canines being very sharply conical and recurved, which are possibly adaptations for securing squid prey. The molars are reduced, barely extending above the gum. The fore flippers have reduced claws and the terminal joints are elongated. The hind flippers have very long cartilaginous extensions: they may reach 22% of the body length, the greatest for any phocid, and appear to drag behind. Pups are dark brown above, paler underneath, and weigh approximately 17–27 kg at birth. They show the striped pattern on the throat characteristic of the adult.

Ross seals make unique "trilling, cooing, and chugging" sounds both in air and underwater. On ice, frequently in response to a disturbance, a Ross seal will raise its head near vertically, arch its back, and inflate the trachea and soft palate with air. Three types of vocalizations are typical: an unvoiced exhalative sound with the mouth open, and, with the mouth and nostrils closed, chugging pulses and siren calls of rising and lowering frequency. These sounds emanate from an expanded throat and chest, evidently owing to the inflation of the laryngeal air sacs. In air the frequencies range from 100 to 1000 Hz, but underwater they may reach as much as 4.5 kHz. The calls stand out well against background noise and are therefore possibly used to indicate location.

Many aspects of the species' behaviour and biology remain unknown because of its relatively low abundance and distribution in pack ice areas, which has limited access. Ross seals breed in the early spring to early summer months. Of nine adult females examined in August and September, 88% were pregnant. Pups each with an accompanying adult female can be seen between 2 October and 15 December with a peak in the period 6–15 November. Since they are generally solitary when encountered, a mating system of serial monogamy rather than polygyny is suggested.

Little is known of the reproductive biology of Ross Seals. The estimated age of sexual maturity is 3–4 years for females and 2–7 years for males. Lactation is thought to last four to six weeks, and is followed by mating and an inferred period of delayed implantation of about 2 months. Although usually solitary during the nonbreeding season, up to five Ross seals have been seen together on the same ice floe. During the spring breeding season they principally occur in regions of heavy, consolidated pack ice. During midsummer they seem to prefer the denser ice types more prevalent in the inner ice pack, but they are also present in open pack ice within the inner reaches, and occasionally on fast ice. Although absent from the outer pack at this time, it has recently been found that they also make prolonged and repeated foraging trips far to the north into the open water. If these trips are typical of Ross seal behaviour they may account for occasional sightings in lower latitudes, such as at Heard Island and southern Australia.

Ross seals hunt within the pack ice, eating mostly midwater squid, but also fish (including Antarctic silverfish) and invertebrates (including euphausids, amphipods, and isopods). The high proportion of empty or nearly empty stomachs of Ross seals during January conforms with the knowledge that the species moults (in January and February) and consequently generally fasts at this time. One study of a female during January showed that she hauled out during the day and dived continually when in the water at night. Dives averaged 110 m deep and 6.4 min long, the deepest and longest dive being 212 m and 9.8 min respectively. Dives were deepest during twilight and shallowest at night as the seals presumably followed the vertical movement of their prey in the water column. However, while out in the open sea through March to September a male Ross seal dived virtually continuously with diving activity fairly evenly distributed throughout 24-hour periods, never exceeding 30 min or 492 m, with dive depths widely and fairly evenly distributed between 12 m and 400 m.

Although the densest concentrations of Ross seals had previously been observed in the southeast Atlantic sector in the King Haakon VII Sea off Dronning Maud Land, data from the early 1990s suggest that Ross seal abundance in that sector declined over the previous 20 years. The population of Ross seals has been estimated to be about 131,000 making it the least abundant Antarctic pinniped.

MARTHÁN BESTER and GREG HOFMEYR

See also **British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); Crabeater Seal; Diving—Marine Mammals; Fish: Overview; Food Web, Marine; Heard Island and McDonald Islands; Leopard Seal; Ross, James Clark; Sealing, History of; Seals: Overview; Weddell Seal; Zooplankton and Krill**

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ROTIFERS

Rotifers are microscopically small inhabitants of freshwater that are characterised by a muscular pharynx, and one or two circles of vibrating cilia (small hairs) on their heads whose synchronized beating gives the appearance of a rotating disc(s) from which their common name—the wheel animalicules—is derived.

Rotifers are found wherever there is freshwater in lakes and pools, in gutters and birdbaths, even in tiny cryosonite holes in glaciers, as well as in the soil and on vegetation, indeed wherever there is a thin film of water. More than 150 different species have been recorded from the Antarctic region out of world total of some 2000.

The first rotifer survey in the Antarctic was carried out by James Murray, the biologist with Ernest Shackleton's British Antarctic Expedition 1907–1909. Since then rotifers have been found throughout the Antarctic region but Murray's pioneering work remains the most interesting. He recorded fifteen species of freshwater rotifer from the McMurdo Sound Area—a mixture of cosmopolitan and endemic species including a number that were new to science.

Of particular interest were *Epiphanes senta* (O. F. Müller) and *Philodina gregaria* Murray. *Epiphanes* *senta* is a cosmopolitan species that is normally found in shallow bodies of water enriched by farmyard animals so that its presence in pools adjacent to penguin and seal wallows in the Antarctic is not really surprising. As a member of the Monogononta it possesses a single gonad and reproduces by cyclical parthenogenesis. Normally the amictic females lay diploid eggs that develop into more amictic females. However, under certain conditions, such as when their habitat is drying up or freezing, mictic females are produced. Mictic females lay haploid eggs that either hatch into males or if fertilized by a male produce resting eggs. Males are very rare and often unlike their females. They are very small, about one half the size of the females, and the digestive system is rudimentary or lacking. The testis and penis are large and during their short lives (they are often only around for one or two days in any year) they endeavour to impregnate as many females as possible. The resulting resting eggs may remain dormant for years, but under the right conditions they hatch into amictic females and thus the cycle begins again.

Philodina gregaria has a pair of gonads and is classified as a Digononta (or bdelloid) rotifer. It is bright red in colour with a pair of conspicuous orange eyespots and is only found on the Antarctic continent and some off-lying islands. It does not occur on South Georgia or any of the other subantarctic islands. Bdelloid rotifers only reproduce by parthenogenesis, and most importantly males do not occur in this group. Most produce eggs that can survive harsh environmental conditions, but *Philodina gregaria* is unusual in that it produces live young. It is an extremely long-lived rotifer—laboratory reared specimens lived for more than three months. During their first month they grow. Thereafter a single offspring is produced every three days so that mothers typically produced up to twenty offspring. Mature adults survive the winter frozen in the pond ice. When the spring thaw occurs they rehydrate and immediately begin reproducing. Enormous populations with densities of many millions of individuals per square metre commonly occur so that they colour the bottom of the pools bright red.

Fast breeding rates, the production of resting eggs and the ability to withstand freezing mean that some species of rotifer are ideally suited to life in the Antarctic. As a result of its ability to respond to changing conditions to survive freezing and thawing *Philodina gregaria* is the archetypal Antarctic invertebrate.

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See also **British Antarctic *(Nimrod)* Expedition (1907–1909); Cold Hardiness; Cryoconite Communities; Microbiology; Soils**

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ROYAL ALBATROSS

Royal Albatross (*Diomedea epomophora,* of the Diomedeidae family within the order Procellariiformes). Two separate taxa, southern *(D. e. epomophora),* and northern *(D. e. sanfordi)*. A large, white-bodied albatross with upper wing black (northern), or mixed black and dusted with white, or white from leading edge with black wingtips (southern), black eyelids, and black cutting edge to bill. Bill coloured horn, but pink when rearing chicks. Main dimensions: wingspan 270–312 cm; body mass 6.25–10 kg. The southern royal albatross competes with the wandering albatross *(D. exulans)* for the title of the world's largest seabird.

The northern royal albatross, breeds at the Sisters and Forty Fours islets at the Chatham islands (99.5% of population) and at mainland Taiaroa Head (0.5%) on New Zealand's South Island, with an estimated total breeding population of 7700 pairs. Nests are built of soil, rock chips, and woody plants on the exposed tops of the islets and headland. Individuals spend over 80% of their life at sea, with regular circumpolar migrations to winter at the southern Chilean and Patagonian continental shelves. The feeding range is primarily over the continental shelf, shelf edge and shelf break to 2000 m depth. The diet consists of cephalopoda (75%–85%) principally *Moroteuthopsis ingens* and *Histioteuthis atlantica,* fish (15%–20%), crustacea, pyrosoma and salps (3%–5%). Migration over deeper waters is very rapid. Classified as Endangered due to its restricted breeding range, and the degradation of their island habitat from storms during the 1980s. Facing a possible population decrease of 50% over three generations unless the habitat improves.

Southern royal albatrosses breed at the Campbell Islands (99%) and Adams, Enderby, and Auckland islands in the Auckland Islands group (1%), with an estimated total breeding population of 8300 pairs. Birds breed on sheltered flattish ground close to ridges, plateaus, and occasionally among scrubby woodlands, with nests of peaty soil and tussock grasses. Similar migratory and feeding zones as the northern royal albatross. Classified as Vulnerable due to its restricted breeding range. The total population is probably stable, but increasing on Enderby Island after extirpation there in the nineteenth century.

Both forms of royal albatrosses lay one egg (380–520 g) in November or December, with incubation lasting 79 days, and fledging taking 225 to 280 days after hatching. This timing ensures that breeders can only breed successfully every 2 years. First return to the natal colony is at 3 or 4 years, with breeding commencing at 6 to 8 years. Some 50%–60% of fledglings survive to breed, with a 5% annual adult mortality. The oldest marked individual reached 62+ years (northern species). "Adolescent" courtship displays occur in groups or "gams" of up to twenty birds for 1 to 2 years before pairing. At least one prebreeding season is spent more quietly "keeping company" with the mate at potential nest sites.

Both taxa have a minor reported interaction with fisheries (trawling and longline). Satellite tracking has demonstrated their ability to travel up to 1800 km in 24 hours during migration, but probably flying for 14 hours daily maximum. Public viewing of the mainland colony at Taiaroa Head attracts more than 300,000 tourists annually.

Christopher J. R. Robertson

See also **Albatrosses: Overview; Auckland Islands; Campbell Islands; Fisheries and Management; Seabird Conservation; Seabird Population and Trends; Seabirds at Sea**

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ROYAL GEOGRAPHICAL SOCIETY AND ANTARCTIC EXPLORATION

One senses that the Royal Geographical Society (RGS) has suffered throughout its existence from a sense of inferiority regarding its more prestigious cousin, the Royal Society, and that this attitude is neither inappropriate nor inaccurate. Without the resources or expected role in the cultural and intellectual life of Great Britain that the Royal Society enjoys, the RGS justly stands in a lesser position. Yet greatness can be defined as narrowing the gap between what one is and what could be, and in this respect the achievements of the RGS regarding exploration in general in the nineteenth and early twentieth centuries, and the exploration of the Antarctic in particular, mark it out for praise and demonstrate even a touch of greatness.

The RGS had been a sponsor and backer of exploration virtually since its founding in 1830. Sir John Barrow, the chairman of the Council of the Society, had used his position as Second Secretary of the Admiralty to become the force behind many Arctic expeditions, and had been a key figure in pushing James Clark Ross's Antarctic expedition of 1839–1843, on which Ross navigated through the ice surrounding the Ross Sea and proceeded to establish a farthest south of 78°10′ S, while discovering the Victoria Land coast, Ross Island, and the Great Ice Barrier (now known as the Ross Ice Shelf).

In the mid-nineteenth century, Sir Roderick Murchison served 16 years as president of the RGS. Under his leadership, the RGS sponsored and helped fund expeditions in many parts of the world, including the Franklin searches in the Arctic and virtually every British expedition to enter Africa during that period. For many of the expeditions sponsored by the RGS—regardless of destination—limited resources were overcome by tenacity.

Apart from Barrow's connections with Ross's expedition, the Society took little part in the exploration of the far south in first two-thirds of the nineteenth century. However, in the "Heroic Era" of Antarctic exploration, the RGS was a crucial leader in developing, sponsoring, and promoting exploration to the Antarctic. Here, a third great leader of the RGS must be singled out as critical to the process: Sir Clements R. Markham (1830–1916), who became president of the Society in 1893 and whose single-minded determination overcame considerable odds during a long struggle to get Britain again involved in Antarctic exploration, leading ultimately to the launch of his dreamed-of expedition.

Markham chose Robert Falcon Scott (1868–1912) to command the British National Antarctic Expedition, and it was Markham who insisted on a purpose built vessel—*Discovery*—which survives to this day in Dundee, Scotland. Markham enlisted every individual and every society that could be of any use in meeting his goal. Early on, he involved a leading academic, John Murray (1841–1914), in the project and eventually persuaded the Royal Society to participate as joint sponsors. Markham was a prime mover in the Sixth International Geographical Congress held in London in 1895, which passed the famous resolution declaring that the exploration of Antarctica was the most important geographical work remaining to be done in the world.

The political influence of the Royal Society was critical in getting H. M. Government to make the grant of £45,000 that allowed Markham's dream to become a reality. For all his efforts and enthusiasm, one is hard-pressed to believe that, without the help of the Royal Society, Markham would ever have seen his great adventure off to explore the far south.

Before the expedition sailed, the RGS and the Royal Society fell out over the issue of science versus adventure. The latter felt that they had lost when Scott was given overall command and the chosen scientific leader, John W. Gregory (1864–1932), resigned from the expedition owing to what he perceived as unfavorable terms for science.

The RGS deserves much of the credit for the successes of the *Discovery* expedition, while its flaws may easily and accurately laid at the feet of Markham, whose devotion to a romanticized memory of the Royal Navy's involvement in the Arctic led him to impose bad advice on Scott.

Following Scott's return to Great Britain, the Society's involvement in further Antarctic exploration and research was severely limited both by the departure of Markham from the presidency and the degree to which his extravagant use of the RGS's funds for the British National Antarctic Expedition impoverished the Society's coffers. The Society provided limited support in terms of finance, equipment, and expertise to later British explorers in the Heroic Era, but several people associated with the RGS remained major players in exploration by their advice and support, notably H. R. Mill (1861–1951) (once the RGS librarian) and J. Scott Keltie, the Society's secretary.

Markham, and therefore somewhat the RGS, was not overly helpful prior to or positive after Ernest Shackleton's British Antarctic Expedition of 1907–1909, and the Society's treatment of Roald Amundsen (1872–1928) upon his return from his successful attainment of the South Pole remains a blot on its history. George Curzon, the Society's president in 1912, made an unfortunate remark about the Norwegian's success and his use of dogs, which justifiably rankled Amundsen.

Yet such incidents cannot diminish the contributions of the RGS to Antarctic exploration. The Society did give support—although modest due to its limited resources—to Scott's second expedition, Douglas Mawson's Australasian Antarctic Expedition, and other exploring efforts throughout the end of the Heroic Era and since.

T. H. Baughman

See also **Amundsen, Roald; Australasian Antarctic Expedition (1911–1914); British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); British Antarctic (*Nimrod*) Expedition (1907–1909); British National Antarctic (*Discovery*) Expedition (1901–1904); Markham, Clements; Mawson, Douglas; Norwegian (*Fram*) Expedition (1910–1912); Ross Ice Shelf; Ross Island; Ross, James Clark; Scott, Robert Falcon; Shackleton, Ernest**

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ROYAL SOCIETY AND ANTARCTIC EXPLORATION AND SCIENCE

The Royal Society of London for Improving Natural Knowledge (RS), founded in 1660, still continues as an independent organization. It has some 1200 Fellows, including both men and women, covering a wide range of disciplines and coming from Commonwealth countries and the Irish Republic, with, additionally, a limited number of Foreign Members of distinction. In the course of time, some twenty Fellows have been directly involved in Antarctica, and the Society itself has played intermittent but considerable roles in supporting investigations in the southern polar regions.

The RS was the first to send professional scientists south of the Equator, Edmund Halley going almost as far as South Georgia in a geomagnetic survey in 1699–1700 at the request of the Society and the expense of the government. This impressed on governments that voyages carried out specifically for scientific purposes might be well worth the cost. Halley's influence on Antarctic research was unintended and indirect, but effective. He had predicted the transit of Venus would occur in 1769, so the RS petitioned King George III for support to observe it from a good position in the South Pacific, and HMS *Endeavour* sailed there under Captain James Cook. With him were the astronomer Charles Green, Joseph Banks, FRS, and Daniel Solander, FRS. Banks was a botanist, a gifted scientist who worked well with Cook. Apart from his astronomical task, Cook had been given secret instructions to look for the hypothetical "Terra Incognita." He found no evidence of it but on his return precipitated a circumnavigation farther south. This penetrated to 71°10′ S in HMS *Resolution,* and obtained the rough outline of the Antarctic continent, although not actually seeing it. On return in 1776, Cook was elected FRS. He had not taken Banks with him because the retinue and paraphernalia that Banks wanted were too much for the ship. Instead Johann Forster, FRS, and his son went and did good work, especially in ornithology. Banks never did reach the Antarctic, but being elected to the highly influential position of President of the RS, which he held for 42 years, he was able to promote future work in the south, including giving help to the Russian Fabian von Bellingshausen, who made an Antarctic circumnavigation in 1819–1821.

However, in general in the first part of the nineteenth century, there was little interest in Antarctica except from sealers. The Royal Navy was most concerned with the Arctic, and among naval officers elected to the RS—26 in 1816–1845—only Captain Henry Forster went to the far south (1828), extending gravimetric observations for the Admiralty but going as far as Deception Island at the Society's request. Then came a burst of activity, centred on terrestrial magnetism and called by William Whewell "by far the greatest scientific undertaking the world has ever seen." Both the British Association for the Advancement of Science and the RS—the latter recalling that the idea dated back to "our illustrious countryman Halley in AD 1701"—resolved that observations should be made in the far south. Edward Sabine, FRS, became the main driving force, and the government agreed to the dispatch of HMS *Erebus* and HMS *Terror* under the command of Captain James Clark Ross, FRS, a veteran Arctic explorer. For use by the expedition, the RS compiled a useful booklet on various topics, notably physics and meteorology. The two ships successfully penetrated the pack ice into what is now the Ross Sea, making spectacular geographical discoveries (1839–1843). The highest mountain seen was named in honour of Ross's friend, Sabine, at that time Foreign Secretary of the RS. Later it was he who worked up the magnetic data and published it in lengthy papers between 1842 and 1868 in the *Transactions of the Royal Society*. A major scientific advance was made by Joseph Hooker, assistant surgeon (later FRS), who in compiling the standard work *Flora Antarctica* rather casually pointed out that phytoplankton is the source of food in the oceans.

Following this there was an "age of averted interest" of nearly 50 years, interrupted only by the voyage of HMS *Challenger* (1872–1876), instigated by the RS and financed by the government. It included only a short incursion through the Antarctic Circle, but its dredging produced important findings about the geology of the continent and the biology of the surrounding seas.

The great revival of interest came with the Sixth International Geographical Congress (1895) proposing an expedition and the RS setting up an Antarctic committee and arranging an international discussion on Antarctic Research (1898). Cooperation with the Royal Geographical Society (RGS) resulted in an unpleasant squabble between Sir Clements Markham, the President of the RGS, who wanted an expedition in naval tradition, and the RS, which backed a scientifically directed venture with exploration in second place. Markham eventually overcame opposition and appointed a naval officer, Robert Falcon Scott, as commander of the 1901–1904 British National Antarctic Expedition. Fortunately Scott was not only an excellent sailor but had scientific insight and empathy with his scientists. He named as the Royal Society Range the high mountains to the west of McMurdo Sound. The scientific output was outstanding, and Scott's second expedition received advice and financial support from the Society.

However, the RS showed no great interest in other expeditions for the next 50 years, although T. W. Edgeworth David, FRS, scaled Mount Erebus and also reached the South Magnetic Pole during Ernest Shackleton's British Antarctic Expedition, on which Douglas Mawson, later to be FRS and leader of Australian expeditions, received his polar initiation. The RS had no formal connection with the marine *Discovery* Investigations (1925–1939), although five of its staff became FRSs, or with the Norwegian–British–Swedish Expedition of 1949–1952.

However, the Society became deeply involved in the International Geophysical Year of 1957–1958 (IGY). As the adhering organisation for the International Council of Scientific Unions (ICSU), it became responsible for the British contribution. Apart from being involved in organisation—managed supremely well by its executive secretary, Sir David Martin—and giving the Falkland Islands Dependencies Survey (becoming the British Antarctic Survey (BAS) in 1961) great assistance, the RS, with government help, set up its own base, one of the first auroral stations, Halley Bay, at 75°31′ S, 26°36′ W, accommodating twenty scientific and technical staff to make upper atmosphere and geomagnetic observations. In 1958, the station was transferred to what was to be BAS.

The RS was involved in setting up the Antarctic Treaty (1961), playing an important role in advising on scientific matters. Its Committee ceased to give advice to BAS when management of that was transferred to the Natural Environment Research Council. The RS continued to arrange exchange of Antarctic scientists between the UK and the USSR (1968), to organise discussion meetings, and to have several Fellows involved in research and international relations. Two directors of BAS, Sir Vivian Fuchs (1974) and Dr. Richard Laws (1980) were elected Fellows. In 2004, the Society had Antarctic representation in the Natural Environment Research Council, Scott Polar Research Institute, Trans-Antarctic Association, and the UK representatives to the Scientific Committee for Antarctic Research.

G. E. FOGG

See also **Antarctic Treaty System; British Antarctic *(Nimrod)* Expedition (1907–1909); British Antarctic Survey; British National Antarctic *(Discovery)* Expedition (1901–1904); *Challenger* Expedition (1872–1876); Cook, James; David, T.W. Edgeworth; *Discovery* Investigations (1925–1951); Fuchs, Vivian; History of Antarctic Science; Hooker, Joseph Dalton; International Geophysical Year; Markham, Clements; Mawson, Douglas; Norwegian-British-Swedish Antarctic Expedition (1949–1952); Russian Naval (*Vostok* and *Mirnyy*) Expedition (1819–1821); Scott, Robert Falcon**

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RUSSIA: ANTARCTIC PROGRAM

The Russian (Soviet) Antarctic Program was created in July 1955 for the USSR participation in the International Geophysical Year (IGY). From the beginning, the Program had two independent sections: (1) expedition, aiming at organizing and conducting monitoring of environmental state parameters, special full-scale scientific experiments, and logistics operations in the Antarctic, and (2) scientific, with the purpose of analyzing and generalizing scientific data collected during the expedition period. Different state executive agencies were charged with supervision of these sections. Prior to the end of the IGY, the leadership in both was entrusted to the USSR Academy of Science, whereas the Main Administration of the Northern Sea Route (Glavsevmorput') of the USSR Ministry of Marine Fleet was responsible for logistics operations. From 1959, Glavsevmorput' was in charge of all expedition objectives of the Soviet Antarctic Expedition (SAE) and the USSR State Committee for Science and Technology (GKNT) for research in the Antarctic. The latter distributed topical research tasks among different Soviet ministries that had research institutions with interests in Antarctic studies. They included USSR Academy of Science, Ministry of Biology, Main Administration of the Hydrometeorological Service under the USSR Council of Ministers (GUGMS), Main Administration for Geodesy and Cartography, and Ministry of Fishery. In the structure of Glavsevmorput', the Arctic and Antarctic Research Institute (AARI) was made responsible for SAE activities.

After the abolishment of Glavsevmorput', AARI was transferred to the GUGMS, preserving its earlier functions concerning the Antarctic, whereas GUGMS and its successors (Goskomhydromet, Roshydromet) were responsible in the executive structure of the country for undertaking all expedition operations in the Southern Polar area.

On August 9, 1992, functions of supervision and control of the Russian Antarctic Expedition (RAE) activity were assigned to Roshydromet by the Decree of the President of the Russian Federation.

In 1992, GKNT was replaced by the Ministry of Science of Russia, which remained in charge of Antarctic studies but with a changed order of financing. Funds were allocated directly to institutes-executors rather than to their agencies. In 1998, in accordance with the Decision of the RF Government, Federal Program "World Ocean" was adopted, with one of its subprograms called "Study and Research of the Antarctic." The subprogram was under the management of the Federal Service of Russia for Hydrometeorology and Environmental Monitoring (Roshydromet), which is currently in charge of the expedition and research activities in the Antarctic.

Almost 50 years of Russian Antarctic studies can be conventionally divided into three stages: study of natural objects, processes, and phenomena in the Antarctic (1955–1969), research for resource exploration in the Antarctic (1970–1991), and determination of the role and place of Antarctica in the global natural and public processes (1992 to present).

During the first stage, an extensive expedition infrastructure was created based on a network of year-round Antarctic stations—Mirny, Vostok, Molodezhnaya, Novolazarevskaya, Bellingshausen, Oasis, Komsomol'skaya, Pionerskaya, and Sovetskaya. A series of inland sledge-caterpillar traverses to the most inaccessible regions of Antarctica were organized. Active aviation operations in the inland areas to investigate the structure of the ice sheet and mountain rock outcrops were carried out. Various oceanographic studies were conducted in the Southern Ocean. The first stage resulted in publication of two volumes of the *Atlas of the Antarctic* (1966–1969).

The resource stage of Antarctic studies was characterized by the large-scale development of expedition activities. The SAE fleet numbered up to eight cargo, research, and passenger ships and oil tankers. In the Pacific Ocean sector, Leningradskaya and Russkaya stations and in Prydz Bay, Progress Base were built. The Soviet stations covered the perimeter of the entire Antarctic continent. The expedition numbered 570 people during wintering and 980 people during summer operations without taking into account crews of ships and aircraft. Large special oceanographic and biological studies of the Southern Ocean were undertaken. Most active were geological and geophysical studies for which field bases Druzhnaya-1, 2, 3, and 4 were arranged. The work of geologists was supported by a large number of aircraft including heavy Il-18 airplane. For operation of such airplanes and Il-76 cargo aircraft, snow-ice air fields that were unique at the time were built at Molodezhnaya and Novolazarevskaya stations. Regular flights were organized via African airports. Extensive materials were accumulated providing support for Soviet ships in the Southern Ocean. Russian geologists collected a large amount of data for evaluating the mineral and hydrocarbon potential of the Antarctic.

The third stage was related to changes in the political-economical life of the country and entry into force of such international law acts as the Protocol on Environmental Protection to the Antarctic Treaty. The network of Russian Antarctic stations decreased to five (Mirny, Vostok, Novolazarevskaya, Progress, and Bellingshausen), and the number of seasonal field bases to two (Druzhnaya-4 and Molodezhnaya). The expedition activities are supported by the R/V *Akademik Fedorov* of Roshydromet and *Akademik Aleksandr Karpinsky* of the Ministry of Natural Resources. The number of expedition participants decreased to ninety people for wintering and eighty for seasonal operations. However, these changes did not influence the character of RAE main research directions. The focus was on the study of modern climate variability, reconstruction of paleoclimate characteristics, dynamics of the mechanisms of development of the "ozone hole" phenomenon, influence of "space weather" (solar wind energy in the interplanetary space) on the character of atmospheric processes, efficiency of technical equipment, and life activity of organisms.

A great deal of attention was given to the problems of Antarctic environment protection aiming both at removal and utilization of waste of the Russian activity during the past decade in Antarctica and introduction of modern technologies preventing its accumulation.

A unique Russian-US experiment on the establishment of the first scientific drifting station in the Weddell Sea in the Southern Ocean called "Weddell-1" can be referred to the studies of this period of activity of Russia. Before that, the international Antarctic community knew nothing like this experiment. The station team consisted of fifteen Russian and seventeen American specialists. A self-contained drift of the ice camp continued from February 12 to June 9, 1992. Over this time, the ice floe passed 750 km to the north with an average drift velocity of 6.6 km day^{-1}, maximum velocity of 25 km day^{-1} (May 24) and minimum velocity of 0.5 km day^{-1} (February 27). The research programs of the drifting station were devoted to physical and chemical oceanography, surface meteorology, ice-cover dynamics, and sea ice biology. The experiments were conducted in the practically unexplored western Weddell Sea. Unique data on the formation of cold bottom water on the Antarctic shelf were obtained. Parameters of heat-mass exchange in the ocean-ice-atmosphere system were determined and a wide range of sea ice cover deformation under the impact of natural forces was investigated. The specific features of biodiversity and factors of habitats of subice ecosystems were revealed.

In the 1990s, deep drilling at Vostok station was intensified in the framework of the Russian-French-American Agreement. As a result the deepest ice borehole in the world with a depth of 3623 m was drilled in 1999. Reconstruction of paleoclimatic changes based on data of this ice core allowed obtaining information on this process over the last 420 kyr.

The broad spread of Russian Antarctic stations allowed Russian specialists to estimate the tendencies of current climate variability and total ozone content over more than 40 years. The tendency for such variability has an ambiguous character for the regions of West and East Antarctica. Thus in the first region, a positive trend of surface air temperature changes is observed, while in the second there is a small negative trend. For the last few years, stabilizing of the "ozone hole" expansion processes and the total ozone decrease in it is noted. An analysis of measurement data indicates a purely natural character of this phenomenon rather than its anthropogenic origin. Importance of geomagnetic and ionospheric observations at the Russian Antarctic stations, especially at Vostok station was recognized long ago by the international community. In the late twentieth century, Russian geophysicists proposed a new integral indicator of the state of geomagnetic perturbations in Earth's polar caps—a "PC-index." Online publication of Vostok data allows estimation of the magnetosphere state not only in the South Geomagnetic Pole area but also in the Arctic, given conjugation of these processes in both hemispheres. A new direction of geophysical studies was investigation of the influence of different nonelectromagnetic origin fields on the peculiarities of life activity of biological organisms, in particular, on the biochemical reaction rates. These fields are most actively manifested in the Antarctic, and studies of their influence on living organisms are becoming increasingly more interesting.

One of the most important projects initiated in the 1990s was that of subglacial Lake Vostok studies. Russia began investigations of the largest Antarctic subglacial water body in 1995 obtaining unique materials on different geographical characteristics of the lake and structure of its bottom sediments. Microbiological studies of the ice core from the low borehole horizons at Vostok station using molecular biology methods turned out to be of the greatest priority. The obtained data not only revealed a possible biodiversity of surface lake water, but also suggested a hypothesis of its riftogenic origin.

The Russian sub-program "Study and Research of the Antarctic" is structurally comprised of five sections: basic studies, scientific-applied studies and developments, environmental monitoring, environmental protection, and logistics support of studies and activities. Specialists of twenty-seven research institutions and universities representing Federal Service for Hydrometeorology and Environmental Monitoring, Ministry of Natural Resources. Ministry of Education and Science, Ministry for Defense, Federal Agency of Geodesy and Cartography, Federal Agency on Fishery and Russian Academy of Science participate in the subprogram projects planned up to 2012. Parameters of RAE activity are determined by the corresponding Decisions of the Government of the Russian Federation for a 5-year period.

VALERIE LUKIN

See also **Antarctic Bottom Water; Antarctic: Definitions and Boundaries; Antarctic Treaty System; Arctic and Antarctic Research Institute, Russia; Ice Core Analysis and Dating Techniques; International Geophysical Year; Ionosphere; Lake Vostok; Ozone and the Polar Stratosphere; Palaeoclimatology; Protocol on Environmental Protection to the Antarctic Treaty; Sea Ice, Weather, and Climate; Solar Wind; South Pole; Subglacial Lakes; Vostok Station**

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RUSSIAN NAVAL (*VOSTOK* AND *MIRNYY*) EXPEDITION (1819–1821)

The Russian expedition to the North and South Poles, and its first division, that is, the South Pole expedition group under the command of Fabian Gottlieb von Bellingshausen on the sloop *Vostok* and transport ship *Mirnyy* (commander Mikhail Petrovich Lazarev), are ascribed special importance in the history of Antarctic exploration, as this expedition is considered to have discovered the Antarctic continent on 28 January 1820 (three days before Britain's Edward Bransfield).

Not a great deal is known about the background of the expedition, and the archival files available (Samarov 1952) do not provide answers to the questions of why the Russian expeditions exploring the Arctic and Antarctic Oceans took place simultaneously, when the idea for them had come into being, and who initiated the concept. The expedition was prepared in a very short period (taking only half a year from the preliminary plan to launching of the four-ship squadron) but cost a great deal (100,000 roubles). In the Russian Empire, it was normal for the financing of exploring expeditions to take years to put into place. The speed with which this expedition was funded lends weight to the belief that Tsar Alexander I had approved it personally. However, the preparations were so hurried that there was not time to get the ships properly ready for a voyage into heavy ice. And the German naturalists who planned to join the expedition soon gave up the idea, as they were not able to get ready in such a short time (having been informed of the expedition only a month before it was launched). Because of the lack of time, the St. Petersburg Academy of Sciences was not able to compile scientific instructions for the expedition, so they were replaced by a set from the Minister of Naval Affairs. Only one scholar, Ivan Mikhailovich

Simonov, Professor extraordinary of astronomy of Kazan University, ultimately participated in the Antarctic part of the expedition.

The Antarctic expedition under von Bellingshausen had two goals: first, to sail as close to the South Pole as possible and discover new lands in this route, and, second, to improve the map of the southern part of the Pacific Ocean and record any new objects in the region.

Both parts of the expedition set off from Kronshtadt on July 16, 1819. In Portsmouth, England, the two groups separated. Von Bellingshausen headed for Tenerife and from there to Rio de Janeiro, which he reached on November 24, 1819. His first objective was to map the southern coastline of South Georgia—which had been discovered by James Cook but remained unmapped—and the hypothetical Sandwich Land. After South Georgia was mapped, on January 3, 1820, the Russians discovered the Traversay Islands group at the north end of the South Sandwich Islands. On January 11, 1820, they determined that Cook's "Sandwich Land" did not exist. Instead, there was a group of islands that von Bellingshausen gave the name South Sandwich Islands. From there, following instructions, they headed south, and in three months (from January to March) von Bellingshausen made six attempts to move through the ice to the South Pole, reaching his farthest south on January 28, 1820 (69°25′ S).

On April 11, 1820, the expedition reached Port Jackson (Sydney, New South Wales), where it was provided with new supplies. On May 19, they sailed for the Tuamotu Islands in the Pacific Ocean in an attempt to discover new islands there. A number of discoveries were made in June 1820. On September 21, 1820, the expedition returned to Port Jackson, where preparations were started for another attempt on the South Pole. On November 12, the anchor was raised and the expedition sailed south to map Macquarie Island.

From the beginning of December 1820 until the end of January 1821, von Bellingshausen made four attempts to approach the South Pole. The most successful was the last. On January 22, 1821, he reached 69°53′ S, 92°19′ W. The same day the Russian expedition discovered the first land—Peter I Øy—south of the Antarctic Circle, which they measured as lying at 68°57′ S, 90°46′ W. On January 29, von Bellingshausen made another discovery, which was given the name the Land of Alexander I (now Alexander Island). The expedition now headed for Brazil to check information forwarded by the Russian ambassador, according to which the coast discovered south of Tierra del Fuego was part of the southern continent. Von Bellingshausen passed through Bransfield Strait (February 5, 1821) and decided that the land that could be seen appeared to be a group of islands. He mapped it and gave Russian names to the South Shetland Islands discovered by William Smith in 1819 and mapped by Bransfield in 1820. From there, the expedition sailed to Rio de Janeiro. It returned to Kronshtadt on August 5, 1821.

Von Bellingshausen's expedition was the second (after Cook) to sail round the Antarctic, circumnavigating the globe at a high southern latitude. The expedition lasted for 751 days, 527 of which were spent on the sea (Shvede 1960). During that time, twenty-nine islands were discovered and mapped, and a vast numbers of observational data were recorded on the natural history, winds, temperatures, water regimes, currents, and ice conditions and types of the Southern Ocean (Bellingshausen 1831). However, European researchers learned so little about those observations that at the beginning of the twentieth century Robert Falcon Scott wrote that "unfortunately, little is known of Bellingshausen's voyage, as the narrative was never translated into English" (Scott 1905). The first German account on the Russian expedition was not published until published in 1842 (Lowe 1842), and it was partly translated into English in 1902. A complete translation into English of the story of von Bellingshausen's expedition did not appear until 1945 (von Bellingshausen 1945).

Although von Bellingshausen did not succeed in going farther south than Cook (who reached 71°10′ S), his expedition obtained the first authentic information on the existence of land south of the Antarctic Circle. Unfortunately, these data, like those of James Clark Ross and other expeditions taking place in the Antarctic in the nineteenth century, were too scanty and scattered to allow scientists to confirm with certainty the existence of a continent in the region of the South Pole. That happened only in the first decade of the twentieth century, when it was proven beyond doubt that an Antarctic continent actually existed. In spite of those discoveries, however, it was not until the 1930s that von Bellingshausen began to be regarded as the discoverer of continent, as the knowledge of the entire outline of the continent was still incomplete. Prior to this, arguments had been made in favour of Edward Bransfield of Britain of Nathaniel Palmer of the United States. The first to draw attention to the fact that on January 28, 1820, the Russians were only 20 miles from the continent and saw the extension of the continental ice shelf of Kronprinsesse Märtha Kyst (discovered in 1929 by a Norwegian expedition under Hjalmar Riiser-Larsen) reaching the Southern Ocean was Frank Debenham in the preface to the English version of von Bellingshausen's narrative (1945). On this basis, he declared that

Russians were the first to discover the Antarctic continent (von Bellingshausen 1945). In the hyperpolitical scholarly world of the Cold War period, this statement gave rise to a very sharp discussion as to what the members of the Russian expedition had actually seen and how they had described it. Today, that debate generally has ceased and it is now almost unanimously accepted that the Russian South Pole expedition discovered the Antarctic continent.

ERKI TAMMIKSAAR

See also **Bellingshausen, Fabian von; Christensen Antarctic Expeditions (1927–1937); Cook, James; Palmer, Nathaniel; Peter I Øy; Riiser-Larsen, Hjalmar; South Georgia**

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SCIENTIFIC COMMITTEE ON ANTARCTIC RESEARCH (SCAR)

SCAR is an interdisciplinary committee of the International Council for Science (ICSU, formerly the International Council of Scientific Unions). SCAR was established in 1957 to initiate, promote, and coordinate scientific research in the Antarctic with a view to framing scientific programmes of circumpolar scope and significance. SCAR also provides independent, international scientific advice to the Antarctic Treaty System.

The seeds of international scientific activities in high southern latitudes can be traced back to 1874–1875, the year of the Transit of Venus when four nations established observatories in the sub-Antarctic. The First International Polar Year was held in 1882–1883 and the Second International Polar Year in 1932–1933 when scientific investigations were confined to the Arctic and sub-Antarctic regions. By 1950, the advances made in all sciences, but particularly in geophysics, encouraged various scientists to propose to ICSU that there should be a third polar year to coincide with maximum activity of the solar cycle. The proposal to ICSU "assumed that the Antarctic region would receive its full share of attention." It quickly became clear that the natural phenomena to be studied required synoptic observations over the whole surface of the Earth. In 1952, ICSU decided that the programme should become global and changed its name to the International Geophysical Year (IGY). At the same time, ICSU formed the Comité Special pour l'Année Géophysique Internationale (CSAGI) to organize the programme.

At the first meeting of CSAGI attention was drawn to the desirability of establishing observing stations on the mainland of Antarctica. Four CSAGI Antarctic conferences were organized to plan the detailed arrangements for the scientific, technical, and logistic activities in the area. At the first of these Antarctic conferences (1955), G. R. Laclavère was elected President and he prefaced the proceedings by emphasizing that the overall aims of the conference were exclusively scientific and that it was not concerned with political questions. Laclavère's statement, adopted by a resolution of the conference, provided a foundation that was adhered to throughout the IGY and ever since has consistently distinguished international scientific activities in the Antarctic organized under the auspices of ICSU.

Fifty-five observatories were engaged in IGY programmes in Antarctica and the sub-Antarctic islands, operated by the twelve nations participating in the Antarctic IGY: Argentina, Australia, Belgium, Chile, France, Japan, New Zealand, Norway, South Africa, Union of Soviet Socialist Republics, United Kingdom, and United States of America.

On a recommendation from the Fourth CSAGI Antarctic Conference in 1957, the Executive Board of ICSU set up an ad hoc committee to examine the merits of continuing general scientific investigations in Antarctica. It recommended that ICSU should establish a committee to continue international organization of scientific activity in Antarctica and the Special Committee on Antarctic Research (SCAR) was established in 1958. Membership comprised a delegate from each nation actively engaged in Antarctic research and representatives of International Geographical Union (IGU), International Union of Geodesy and Geophysics (IUGG), International Union of Biological Sciences (IUBS), and International Union of Radio Science (URSI).

The first meeting of SCAR was held at The Hague, 3–5 February 1958, when the foundations were laid from which the committee—the title of which was altered to the Scientific Committee on Antarctic Research in 1961—has developed. SCAR has met biennially since the VIII SCAR Meeting in 1964.

For SCAR, the Antarctic region is considered to include Antarctica, its offshore islands, and the surrounding ocean including the Antarctic Circumpolar Current, the northern boundary of which is the Subantarctic Front. Île Amsterdam, Île St. Paul, Macquarie Island, and Gough Island lie north of the Subantarctic Front but are also within SCAR's area of interest.

The main purpose of SCAR is to provide a forum for scientists of all countries with research activities in the Antarctic to discuss their field activities and plans and to promote collaboration and coordination between them. The biennial SCAR meeting is held over two weeks with the scientific disciplinary subgroups meeting in the first week and reporting to the SCAR Delegates in the second week when scientific and administrative decisions are made. The membership of SCAR has grown over the years from the original twelve countries taking part in the IGY to a current (2005) total of twenty-eight Full Members and four Associate Members.

All SCAR Members send active Antarctic scientists as representatives to the Standing Scientific Groups (formerly Working Groups) in those fields where they have ongoing research programmes. National research programmes are discussed and, where appropriate, are coordinated to give greater scientific value and more cost-effective logistic support. Some discussions lead to proposals for major international research programmes and these are put to the Delegates' Meeting for consideration. If a programme is accepted a group of scientists will be established to develop full science and implementation plans. These then become SCAR Scientific Research Programmes and the group will coordinate the national research inputs to these programmes. Progress is monitored through workshops and reported to SCAR, and results are presented at SCAR scientific symposia and other international fora.

SCAR has currently five major Scientific Research Programmes that will contribute to the major research effort of the forthcoming International Polar Year (IPY). The programmes are Antarctic Climate Evolution (ACE); Antarctica and the Global Climate System (AGCS); Evolution and Biodiversity in the Antarctic (EBA); Inter-hemispheric Conjugacy Effects in Solar-Terrestrial and Aeronomy Research (ICESTAR); and Subglacial Antarctic Lake Environments (SALE).

SCAR's greatest achievement has been the Biological Investigations of Marine Antarctic Systems and Stocks (BIOMASS) programme. The programme was proposed in 1968 "to gain a deeper understanding of the structure and dynamic functioning of the Antarctic marine ecosystem as a basis for the future management of potential living resources." In 1980–1981, thirteen ships from eleven nations took part in the First International BIOMASS Experiment (FIBEX); a second (SIBEX) field season took place in 1983–1984. The BIOMASS data provided the fundamental dataset for the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR).

For the Antarctic Treaty System, SCAR provided the basis for the Agreed Measures for the Conservation of Antarctic Fauna and Flora, subsequently subsumed in the Protocol on Environmental Protection to the Antarctic Treaty. SCAR provides advice on Management Plans for protected areas and on Comprehensive Environmental Evaluations (CEEs). SCAR also responds to requests from the Antarctic Treaty on a wide variety of scientific matters that are within its competence.

List of Acronyms and Abbreviations

ACE	Antarctic Climate Evolution
AGCS	Antarctica and the Global Climate System
BIOMASS	Biological Investigations of Marine Antarctic Systems and Stocks
CCAMLR	Commission for the Conservation of Antarctic Marine Living Resources
CEE	Comprehensive Environmental Evaluations
CSAGI	Comité Special pour l'Année Géophysique Internationale
EBA	Evolution and Biodiversity in the Antarctic
FIBEX	First International BIOMASS Experiment
ICESTAR	Inter-hemispheric Conjugacy Effects in Solar-Terrestrial and Aeronomy Research
ICSU	International Council for Science (formerly International Council of Scientific Unions)

IGU	International Geographical Union
IGY	International Geophysical Year
IPY	International Polar Year
IUBS	International Union of Biological Sciences
IUGG	International Union of Geodesy and Geophysics
SALE	Subglacial Antarctic Lake Environments
SCAR	Scientific (formerly Special) Committee on Antarctic Research
SIBEX	Second International BIOMASS Experiment
URSI	International Union of Radio Science

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See also **Amsterdam Island (Île Amsterdam); Antarctic Treaty System; Circumpolar Current, Antarctic; Conservation of Antarctic Fauna and Flora: Agreed Measures; Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); International Geophysical Year; International Polar Years; Macquarie Island; Protocol on Environmental Protection to the Antarctic Treaty; St. Paul Island (Île St. Paul)**

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SCIENTIFIC COMMITTEE ON OCEANIC RESEARCH (SCOR)

SCOR was created by the International Council for Science (ICSU) in 1957 to promote international cooperation in ocean sciences. Most of the nations that conduct extensive research in ocean science participate in SCOR. SCOR is directed by its Executive Committee, composed of officers elected by SCOR members and augmented by ex officio members from the International Association for the Physical Sciences of the Oceans, the International Association of Biological Oceanography, and the International Association for Meteorology and Atmospheric Sciences.

SCOR has sponsored five working groups relevant to the Southern Ocean. For example, the Scientific Committee on Antarctic Research (SCAR), SCOR (as SCOR Working Group 54), IABO, and FAO Advisory Committee on Marine Resources Research formed the Biological Investigations of Marine Antarctic Systems and Stocks (BIOMASS) Programme in 1976. This program's principal objective was to improve our understanding of the Antarctic marine ecosystem to enable management of the living resources of the Southern Ocean (El-Sayed 1994). BIOMASS was prolific in its production of reports and handbooks during its almost 10-year existence, contributing significantly to our knowledge of Southern Ocean ecology and providing a foundation for later SCOR-sponsored research projects such as the Joint Global Ocean Flux Study (JGOFS) and the Global Ocean Ecosystem Dynamics (GLOBEC) project. SCOR Working Group 74 on General Circulation of the Southern Ocean was formed in 1982 to (1) identify major gaps in the knowledge of the general circulation of the Southern Ocean, bearing in mind its relevance to biology and climate; and (2) to specify physical and chemical programs to investigate the Southern Ocean. The working group issued its findings in SCOR (1986), which contributed to the World Ocean Circulation Experiment (WOCE).

SCOR and the International Geosphere-Biosphere Programme (IGBP) have cosponsored two large-scale research projects with Southern Ocean activities in the past two decades: JGOFS and GLOBEC. JGOFS sponsored a Southern Ocean research program in 1991–1999, which helped improve our understanding of the role of the Southern Ocean in the global carbon cycle (Baliño, Fasham, and Bowles 2001). Southern Ocean GLOBEC (still ongoing) has brought together scientists from several nations and from the International Whaling Commission to study the year-round life cycle of Antarctic zooplankton, particularly krill, as well as predators of krill, such as marine mammals and seabirds (Barange and Harris 2003). This project is notable for its conduct of observations and research in every season, including the Antarctic winter. SCOR and other organizations are establishing three new research projects that will have Southern Ocean components: the GEOTRACES project (a study of the global cycling of trace elements and isotopes), the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) project, and the Surface Ocean–Lower Atmosphere Study (SOLAS). SCAR and SCOR have formed an Expert Group on Oceanography to encourage an interdisciplinary approach to Southern Ocean observations, modeling and research, recognizing the interdependence of physical, chemical and biological processes in the ocean at present and in the past.

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See also **Global Ocean Monitoring Programs in the Southern Ocean; International Geosphere-Biosphere Programme (IGBP); International Whaling Commission (IWC); Scientific Committee on Antarctic Research (SCAR); Southern Ocean; Zooplankton and Krill**

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SCOTIA SEA, BRANSFIELD STRAIT, AND DRAKE PASSAGE, OCEANOGRAPHY OF

The Scotia Sea is a region of the South Atlantic Ocean lying between the Antarctic Peninsula, South Georgia, and Tierra del Fuego, and named after the ship used in these waters by the Scottish National Antarctic Expedition (1902–1904). With an area in excess of 900,000 km^2 and an average depth of approximately 3800 m, it sits within a complex and tectonically active marine basin bounded to the south, east and north by the island-dotted Scotia Ridge. Nearly all of the Scotia Sea rests on its own tectonic plate (the Scotia plate), with only its eastern extremity forming part of the South Sandwich microplate. Deep passageways in the Scotia Ridge communicate the Scotia Sea with the adjoining ocean basins. Most notably, the Orkney Passage leads southward into the Weddell Sea, the Georgia Passage eastward into the wider South Atlantic, and the Shag Rocks Passage northward into the Malvinas Chasm and beyond, into the Georgia and Argentine basins. The Scotia Sea opens to the west into the South Pacific Ocean in a 600 mile (1000 km) wide and typically less than 4000 m deep waterway known as the Drake Passage. At the southern end of this passage, the 70 mile (120 km) wide, relatively shallow Bransfield Strait extends as a semienclosed sea over 50,000 km^2 between the South Shetland Islands and the Antarctic Peninsula.

Ocean Circulation

The oceanographic conditions of the Scotia Sea are shaped by the presence in the region of two of the major current systems of the southern hemisphere. First and foremost, the Antarctic Circumpolar Current (ACC) is a vigorous, primarily wind-driven, deep-reaching eastward flow that conveys approximately 140 million m^3 s^{-1} of water around Antarctica and enters the Scotia Sea through Drake Passage, sweeping the region from southwest to northeast. The ACC is not a homogeneous current, but is organized into several strong jets that are steered by submarine topography and reach typical peak velocities of 20–60 cm s^{-1}. These jets are associated with oceanic fronts, or thin bands across which the properties or depth of water masses change sharply. The ACC has three fronts that define many of the main circulation pathways in the Scotia Sea: the Subantarctic Front, which is the ACC's northern boundary and skirts the South American continental slope; the Polar Front, which accounts for most of the ACC's transport of water through the region and follows a curving trajectory from the central Drake Passage to Shag Rocks Passage; and the Southern ACC Front, which is the most tenuous and southerly of the three fronts and exits the region south of South Georgia. The reasons for the frontal zonation of the ACC are not well understood, but current evidence points to an explanation involving the Earth's rotation, topographic steering, and external forcing (e.g., by winds and sea ice). The ACC frontal jets are renowned for being highly variable in strength and location, forming meanders and eddies often as a result of internal instabilities or interaction with the ocean floor.

South of the ACC, the northern limb of the Weddell Gyre flows northeastward in the vicinity of the South Scotia Ridge. The gyre conveys water that broke off the ACC to join the clockwise Weddell Gyre circulation well to the east of the Scotia Sea (near 30° E), and that has been cooled, freshened, and ventilated (i.e., enriched in atmospheric gases) by interaction with near-freezing water over the continental shelves of the Weddell Sea. This influence is most pronounced in a vertically homogeneous, well-ventilated zone termed the Weddell-Scotia Confluence, which emanates from the Antarctic Peninsula and extends eastward for over 2500 miles (4000 km) to around 20° E. Cascading of Weddell Sea shelf water off the northern tip of the peninsula and subsequent mixing with warmer, more saline deep water masses are implicated in the formation of the Confluence. These processes are also central to forming the water masses of the Bransfield Strait, with the inflow of ACC water through gaps in the South Shetland Islands playing a lesser role. The circulation of the Bransfield Strait and the formation of the Weddell-Scotia Confluence are, in fact, closely related, as the northeastward flow of Bransfield Strait water masses along the northern rim of the Strait (known as the Bransfield Current) feeds the emergence of the Confluence.

Concurrent with the vigorous, northeastward currents that dominate the Scotia Sea circulation, a weaker flow exists that transports water masses across the region along an approximately north-south axis. This flow arises from a complex interplay between wind- and eddy-driven currents and, at typical speeds of 0.1–1 cm s^{-1}, it is roughly a factor of 10–100 slower than the ACC. The flow is the manifestation of the Southern Ocean component of the global thermohaline circulation, the great conveyor belt that circulates heat, carbon, and other tracers of climatic significance around the Earth as it slowly overturns the ocean. The distribution of water masses in the Scotia Sea largely reflects the thermohaline circulation. Thus, the bulk of the deep ACC is occupied by the relatively warm and saline Circumpolar Deep Water (CDW), a water mass that originally sinks to the abyss in the North Atlantic and that advances southward and upward across the ACC in the Scotia Sea. CDW is commonly classified into an Upper and a Lower variety with distinct properties. The shallower Upper class is characterized by a minimum in dissolved oxygen concentration that can be traced back to respiration by marine organisms in the South Pacific and Indian oceans, and that is therefore indicative of northward CDW excursions in those basins. The Lower class is in turn defined by a maximum in salinity attributable to the North Atlantic origin of the water mass. Whereas this characterization of Upper and Lower CDW is applicable circumpolarly, more subtle properties of the water mass in Drake Passage denote two peculiarities of the thermohaline circulation in the region: (1) a deep water mass from the subtropical South Pacific Ocean enters the ACC's CDW layer in northern Drake Passage after flowing southward along the western slope of South America; and (2) Lower CDW in the southern ACC mixes intensely with and entrains Ross Sea bottom waters closely upstream of Drake Passage. Further downstream, as it flows through the Scotia Sea, the CDW in the ACC is ventilated, cooled, and freshened by mixing with a colder, less saline type of CDW found in the Weddell-Scotia Confluence.

While CDW moves southward and upward across the ACC in the Scotia Sea, a number of water masses translate northward and downward in the return limb of the global thermohaline circulation. The relatively cold and fresh Weddell Sea Deep Water (WSDW) is formed in the southern and western Weddell Sea as Lower CDW mixes with near-freezing water over the continental shelves of the region. About 5 million m^3 s^{-1} of WSDW enter the Scotia Sea by spilling over the South Scotia Ridge (mainly through the Orkney Passage) and subsequently fill the basin's abyss. WSDW then undergoes intense mixing with overlying Lower CDW and contributes to the ventilation of this water mass in the ACC, ultimately escaping the Scotia Sea by flowing eastward through Georgia Passage. The significance of this stream of WSDW running through the Scotia Sea resides in its representing a considerable fraction (in the region of 20%–30%) of all the Antarctic bottom waters exported northward from the high-latitude Southern Ocean. These waters ultimately invade the abyss of much of the ocean and embody the deepest and coldest layers of the global thermohaline circulation.

Above the Upper CDW, a thin (100–200 m), fresh surface layer of Antarctic Surface Water (AASW) flows northward across the ACC driven by the prevailing westerly winds. This surface flow is fed by the upwelling of CDW in a broad zone situated around the southern edge of the ACC that is often referred to as the Antarctic Divergence. When AASW crosses the Polar Front, it gradually plunges downward and contributes to the formation of Antarctic Intermediate Water (AAIW) north of the Subantarctic Front. Whilst this process is widespread around the ACC, it exhibits some regional peculiarities in the Scotia Sea. There, two varieties of AAIW occur with different temperatures and densities. The colder, denser AAIW shows evidence of having been formed from AASW, as outlined above. In turn, the warmer, lighter AAIW is also influenced by an alternative formation process involving strong atmospheric cooling and deepening of the upper ocean mixed layer in winter. This mechanism is most compellingly manifested in the production of the overlying Subantarctic Mode Water immediately upstream of Drake Passage. The distinction between the two types of AAIW is preserved as they flow through the Scotia Sea following the South American continental slope. They are then modified in the Argentine Basin by mixing with surrounding water masses and, together with Subantarctic Mode Water, go on to ventilate the intermediate layers of much of the Atlantic Ocean.

Climate

The climate of the Scotia Sea is generally cold and stormy with year-round intense westerly winds. Air temperatures and precipitation are moderately low (typically, –1°C to 5°C and 300–700 mm yr^{-1} in the annual average) and exhibit a relatively narrow annual range. Geographical variations in the climate of the Scotia Sea are largely controlled by the banded ocean circulation that characterizes the region. The atmospheric jet stream crosses the Scotia Sea in broadly the same direction as the ACC and, as a result, there are striking climatic contrasts across the different frontal zones. This is most clearly illustrated by the distinct climates of the Falkland Islands and South Georgia, two island clusters located at broadly the same latitude but on different ACC frontal zones. The Falklands lie on the equatorward flank of the Subantarctic Front and, accordingly, have a maritime climate with cool temperatures and moderately low precipitation. South Georgia, on the other hand, sits poleward of the Polar Front and endures a harsher climate with annual-mean subzero temperatures, abundant snow, and extensive glacial cover. The oceanic control of the regional climate also transpires in a similarly pronounced climatic contrast between the northern reaches of Drake Passage and the Bransfield Strait.

The most apparent expression of a seasonal cycle in the climatic conditions of the Scotia Sea is provided by sea ice. But for localized sea ice pockets near some of the islands and in the Bransfield Strait, the Scotia Sea is generally sea ice–free at the height of summer. However, as autumn progresses, low air temperatures cause the ocean surface to freeze and the Antarctic sea ice tongue advances northward from the Weddell Sea to cover the southern third of the Scotia Sea (around 300,000 km^2), occasionally reaching as far north as South Georgia. Melting ensues in spring and the ice tongue retreats southward. The resulting cycle of freezing and melting affects the properties of the surface waters in the southern ACC and the Weddell-Scotia Confluence in ways that are significant for both the thermohaline circulation and the regional ecosystems. The southern Scotia Sea also hosts the passage and melting of numerous icebergs, most of which are detached from the Weddell Sea ice shelves to the south and transported to the region by the Weddell Gyre.

Superimposed on this background, seasonally evolving climatic state, a number of large-scale modes of southern hemisphere climate variability modulate the Scotia Sea climate over periods of months to decades. Amongst these, the Semiannual Oscillation (SAO) and the Southern Annular Mode (SAM, also known as the Antarctic or Southern Oscillation) are the most prominent. The SAO is a twice-annual intensification and weakening of the circumpolar trough of low sea level pressure around Antarctica and arises from the differing annual march of atmospheric temperatures over Antarctica and the midlatitude Southern Ocean. It is a strong driver of semiannual variability in a wide range of climatic parameters of the Scotia Sea, including sea surface temperature, precipitation, and the strength of the winds. The SAM instead reveals itself as a circumpolarly coherent seesaw in sea level pressure between high latitudes and the subtropics, resulting in westerly wind anomalies centred approximately along 60° S. The strength of the Scotia Sea winds fluctuates with a wide range of frequencies in response to the SAM, which also affects regional precipitation patterns, sea surface temperatures, and sea ice extent. It is through their influence on wind strength that the SAO and the SAM modulate the oceanic flow at all depths too, with the transport of water through Drake Passage varying by several million $m^3\ s^{-1}$ in a near-instantaneous reaction to changes in the wind. Further, the SAM is itself affected by a number of mechanisms of tropical climate variability (such as the Madden-Julian Oscillation, the dominant mode of intraseasonal variability in the tropical atmosphere) and thereby mediates the remote forcing of the Scotia Sea climate by the tropical atmosphere-ocean system.

Other mechanisms of remote modulation of the Scotia Sea climate operate in relative isolation from the SAM. The most significant example of these is provided by the El Niño Southern Oscillation (ENSO), a sporadic, several-season-long disruption of the ocean–atmosphere system in the tropical Pacific Ocean that regulates Scotia Sea climate in a variety of ways. For example, ENSO has been shown to affect atmospheric and upper ocean properties over the Scotia Sea via a near-instantaneous atmospheric teleconnection to the tropical Pacific. Additionally, ENSO influences sea ice extent and atmospheric and upper ocean properties in the Scotia Sea with much longer temporal lags. On the one hand, a lag of about 3 months results from the impact of ENSO events on the state of the Antarctic Dipole, a stationary wave pattern in climatic conditions reflecting a seesawlike relationship between Pacific and Atlantic polar regions. On the other, a 3-year delay arises from the time that the ACC takes to convey oceanic anomalies from their source region in the South Pacific, where ENSO variability is extended to midlatitudes by a train of large-scale atmospheric waves termed the Pacific–South American pattern.

Marine Ecosystems

The surface waters of the Scotia Sea, like those of many other Southern Ocean regions, are very rich in nitrate, phosphate, and silicate, the basic nutrients required to support marine plant life. This feature of the Scotia Sea environment is attributable to the large-scale upwelling of nutrient-rich CDW in the Antarctic Divergence and its subsequent northward transport as AASW. In spite of the abundance of nutrients, the biomass of phytoplankton (i.e., microscopic floating plants) in the Scotia Sea is modest and primary production (the assimilation of carbon by phytoplankton during photosynthesis, estimated at 50–200 grams of carbon per m^2 per year over much of the region) is moderate by global standards, although they are both elevated in relation to other deep Southern Ocean basins. The reasons for this apparent paradox are not fully understood, but likely involve one or a combination of two factors: (1) the poor light environment resulting from the considerable depth of upper ocean mixed layers in the Scotia Sea over much of the year, which has a negative impact on the phytoplankton's capacity to photosynthesize; and (2) the severe scarcity of dissolved iron, a nutrient that is needed in small concentrations for the chemical reactions of photosynthesis. In certain instances, one or both of these limiting factors are relieved and phytoplankton blooms occur that account for the bulk of the annual primary production in the Scotia Sea. Most conspicuously, phytoplankton thrives in shelf seas throughout the basin, the Bransfield Strait and along the Weddell-Scotia Confluence during spring and summer, in response to the seasonal thinning of the upper ocean mixed layer and the local availability of iron from sediment sources or ice melt. Often, primary production is also enhanced more subtly and patchily in the vicinity of ACC frontal jets and eddies, where the deficiency of light or iron may be alleviated by localized upwelling.

Sustained by its relative richness in phytoplankton biomass, the Scotia Sea hosts the highest concentrations of Antarctic krill *(Euphausia superba),* a keystone zooplankton (i.e., microscopic floating animals) species in the Southern Ocean ecosystem that is vital to the diet of many Antarctic predators (principally, whales, seals, squid, toothfish, icefish, penguins, albatrosses, and other flying bird species). It has also been the target of a large multinational fishery since the 1970s that yields an annual catch of approximately 100,000 tonnes at present. The stock of krill in the Scotia Sea (estimated at approximately 44 million tonnes) is, however, not self-sustaining. Rather, the krill are thought to originate in spawning grounds on the Antarctic Peninsula shelves (mainly between January and March), from which they are transported in swarms into the southern and eastern fringes of the Scotia Sea by the Weddell-Scotia Confluence and the southern ACC. The krill life cycle develops as they flow away from their native coastal waters and spans up to seven years. This itinerant lifestyle makes the krill population in the Scotia Sea very sensitive to environmental change. Accordingly, large interannual fluctuations in the abundance of krill in the region occur in response to changes in climatic conditions around the krill spawning grounds, partially associated with the previously outlined large-scale modes of southern hemisphere climate variability. A striking illustration of this sensitivity is the observation of a decline of krill biomass in the Scotia Sea and its substitution by other zooplankton species since the 1970s. This is apparently connected to the long-term reduction of sea ice cover around the Antarctic Peninsula, which implicates the loss of the krill's winter habitat and food supply. Owing to the unusual shortness of the Antarctic marine food chain, the abundance and distribution of higher predators in the Scotia Sea are largely shaped by those of krill and, to a certain extent, exposed to the same interannual variability. The environs of the Antarctic Peninsula, the southern Scotia Sea, the South Sandwich Islands and South Georgia thus support some of the largest populations of these predators anywhere around Antarctica. Other zooplankton species in the krill, salp, and copepod orders are found in the Scotia Sea in relatively high concentrations, but their function in the regional ecosystem is less significant.

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See also **Antarctic Bottom Water; Antarctic Divergence; Antarctic Intermediate Water; Circumpolar Current, Antarctic; Circumpolar Deep Water; Eddies in the Southern Ocean; Food Web, Marine; Phytoplankton; Polar Front; Scottish National Antarctic Expedition (1902–1904); Sea Ice, Weather and Climate; Southern Ocean: Climate Change and Variability; Southern Ocean: Fronts and Frontal Zones; Southern Ocean: Vertical Structure; Teleconnections; Thermohaline and Wind-Driven Circulations in the Southern Ocean; Weddell Sea, Oceanography of; Zooplankton and Krill**

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SCOTT POLAR RESEARCH INSTITUTE

The Scott Polar Research Institute (SPRI) was founded in 1920 as a memorial to Robert Falcon Scott and his four companions—Lieutenant Henry R. Bowers, Petty Officer Edgar Evans, Captain L. E. G. Oates, and Dr. Edward Wilson—who died on their return journey from the South Pole in 1912. The idea for a "polar centre" was first raised on the slopes of Mount Erebus in November 1912 by two geologists on Scott's last expedition, Frank Debenham and Raymond Priestley. Debenham eventually wrote an outline of the idea and in 1919 sent his proposal for the founding of a polar institute to Sir William Soulsby of the Captain Scott Memorial Mansion House Fund, which had been set up by donations made by the British people in response to Captain Scott's final request: "for God's sake look after our people." The money raised was intended to be distributed amongst a number of recipients, including a Polar Research Fund.

With the assistance of Sir Arthur Shipley, Master of Christ's College, a grant was offered to Cambridge University to pay for a polar wing of a proposed new Geography Building. The Institute dates from the acceptance of this grant on 20 November 1920. Temporary accommodation was found in the Sidgwick Museum, where a collection of equipment, records, and books began to accumulate. The prospects of a new Geography Building faded, however, and the Trustees of the Captain Scott Fund made money available for the erection, endowment, and maintenance of the Scott Polar Research Institute. In 1934, the Institute moved to its present site on Lensfield Road, where its original historic building has been augmented by additional laboratory, library, and office space in 1968 and 1998.

Debenham served as the Institute's original director, and amongst his successors were Launcelot Fleming and Colin Bertram, both members of the British Graham Land Expedition (BGLE) 1934–1937, and Gordon Robin, a member of the Norwegian–British–Swedish Antarctic Expedition (1949–1952), who served as director from 1958 to 1983. Robin, a geophysicist and glaciology, together with his social-science colleague Terence Armstrong, developed the Institute into an important centre for academic research within Cambridge University. Others influential in the history of the Institute include Priestley, James Wordie, who had accompanied Ernest Shackleton on the Imperial Trans-Antarctic Expedition (1914–1917), and Brian Roberts who took part in the BGLE and was an important member of the

Foreign and Commonwealth Office and the Institute for many years.

Today, the Institute comprises about fifty staff and students and is a subdepartment in Cambridge University. Its main activities are, on the one hand, research into science and social science issues in both the Antarctic and Arctic and, on the other, a polar library and information service, together with rich holdings of polar historical manuscripts, artefacts, works of art, and photographs. It also has a polar museum in which themed selections of these broad and deep collections are displayed as part of its public outreach and education programme. The Institute's journal, *Polar Record,* is the oldest journal dedicated to polar research in the world, having begun publication in 1931. SPRI is also host to the secretariats of the International Glaciological Society (IGS) and the Scientific Committee on Antarctic Research (SCAR).

The scientific research of the Institute is currently centred on the investigation of glaciers and ice sheets and the surrounding polar seas, and the ways their behaviour is linked to environmental change at a global scale. A central theme is the response of ice sheets and glaciers to climate warming and the effects that melting ice has and will have on global sea level. Remote sensing from aircraft and satellites is a major investigative tool, and the Institute is well known, for example, for the development of radar techniques to measure the thickness of ice, and, in particular, the first comprehensive mapping of the thickness of the 13.7 million km^2 Antarctic Ice Sheet. Members of the Institute's staff also have considerable expertise in the history of the polar regions, and of social, economic, and political issues. In the Antarctic context, there is expertise in, for example, the history of geographical and scientific exploration of Antarctica and in the development of the Antarctic Treaty. There is an MPhil course in Polar Studies, which has both physical- and social-science pathways.

The SPRI Library has collections of both rare and contemporary books, journals, and papers on Antarctica that are unrivalled internationally, forming a research library and polar information service that is used by scholars worldwide. The Institute also holds, in its temperature and humidity controlled Archives, a very wide range of manuscripts and documents concerning the polar regions. Examples include Shackleton's personal diaries from his Antarctic expeditions and the last letters written by Scott, Wilson, and Bowers from their fateful camp on the Ross Ice Shelf. The Picture Library holds a wide range of photographs and negatives from the "Heroic Era" of Antarctic exploration, including annotated albums by Herbert Ponting and Frank Hurley, and more than 1000 original glass-plate negatives taken by Ponting on Scott's last expedition. These are iconic early photographs that first formed public perceptions of the Antarctic continent. The SPRI Polar Museum has displays concerning both contemporary polar scientific work by Institute staff and the history of the polar regions. Items include the reindeer skin sleeping bag used by Captain Oates, Roald Amundsen's written measurements of the position of the South Pole, and Frank Worsley's log from the boat journey of *James Caird* from Elephant Island to South Georgia. Among the artworks held at SPRI are several hundred watercolour paintings by Edward Wilson.

Julian A. Dowdeswell

See also **British Antarctic *(Terra Nova)* Expedition (1910–1913); British Graham Land Expedition (1934–1937); Debenham, Frank; History of Antarctic Science; Imperial Trans-Antarctic Expedition (1914–1917); Norwegian–British–Swedish Antarctic Expedition (1949–1952); Oates, Lawrence Edward Grace; Photography, History of in the Antarctic; Priestley, Raymond; Scott, Robert Falcon; Wilson, Edward; Wordie, James**

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SCOTT, ROBERT FALCON

For most of the twentieth century, Robert Falcon Scott (1868–1912) was one of the greatest British heroes. His glorious death returning from the pole seemed the culmination of the Victorian tragic hero. A book by Max Jones discusses how Scott's memory served to inspire his fellow Britons through the decades after his death.

In 1979, the publication of *Scott and Amundsen* by Roland Huntford changed the impression that many people held of Scott. Huntford praised the Norwegian explorer but missed no opportunity to castigate his counterpart, upon whom Huntford heaped scorn and condemnation. Regrettably, despite Huntford's undeniable brilliance and scholarship, his view of Scott is deeply flawed. Seen in the context of his time and his mentors, principally Sir Clements Markham (1830–1916), Scott emerges as a naval officer and polar explorer who was capable of inspiring great devotion in his followers and of accomplishing important scientific work in the polar regions.

Scott made his career in the Royal Navy, but he languished without distinction until two events changed the course of his life: his sister married a high-ranking naval officer after which Scott's own career took a turn for the better, and he was selected to command the National Antarctic Expedition, the *Discovery* expedition (1901–1904). His appointment was not without opposition but Markham was an inveterate schemer and was able to cobble together the votes within the guiding committee to secure Scott's appointment. One immediate result was the resignation of the scientific director, J. W. Gregory (1864–1932) from the expedition. While the scientific accomplishments of this endeavor were considerable, Gregory's participation might have advanced the development of the continental drift theory.

The *Discovery* expedition was forced to stay an additional unexpected year because the vessel was caught in ice. Relief ships that came to Scott's aid freed his ship and the whole party returned to Great Britain in 1904. Scott published a highly regarded account of the endeavor and resumed his naval career, noting publicly that his polar career was over.

Scott was not alone in being drawn back to the magic of the south polar regions and in 1909 he announced his intention to launch a second expedition to complete the scientific work his team had begun on the first trip and to reach the South Pole.

This second endeavor included two important land journeys. Over the winter E. A. Wilson led two others in the deadly cold and darkness to seek the egg of the Emperor penguin. Wilson thought (mistakenly) that this discovery would unlock secrets related to evolution. This horrific journey in which temperatures averaged –55°F has never been surpassed in the annals of polar endurance.

The attempt on the South Pole was complicated by the arrival in the Antarctic of Roald Amundsen (1872–1928) who detoured en route to a drift across the Arctic to launch an assault on the South Pole using the expertise he had gained in previous polar work. Thus a race was forced upon Scott, one he was ill equipped to win, especially when bad conditions in the fall before his south polar journey had forced him to place an important depot 30 miles north of his original intention.

Although much has been made of the foolishness of using ponies for transport, one does well to remember that Sir Ernest Shackleton nearly made it to the pole in 1909 using ponies and that, thanks to the determination and hard work of Captain L. E. G. Oates, Scott's ponies got as far as he planned for them to go on the southern journey.

Scott's planning was deeply flawed in the sense that he refused to profit from the experience of others who had demonstrated that dogs could thrive in Antarctic conditions. Ultimately, Scott distrusted all animal support and put his faith in manhauling, a means of transport that relied on grit and determination, conditions over which Scott felt he could have some control.

Even as they marched southward, Scott had not announced who would be in the final four to the pole. Twelve men in three groups trudged step-after-step, two groups of four working in support for the final party that would complete the journey. Scott sent one team back and when it came time to send the second one back, he made a fateful decision. He asked his second-in-command Lt. E. R. G. R. Evans (1881–1957) if he would spare H. R. "Birdie" Bowers from his team so Bowers could join the polar party. Evans had little choice but to agree and headed back in the company of two seamen, Petty Officers William Lashly and Tom Crean.

Evans's threesome nearly did not make it. Evans came down with scurvy and his bluejackets had to take care of him and pull the sledge in his place when he became incapacitated. Eventually, Evans ordered his men to leave him to save themselves. In an action totally in opposition to how they had lived their entire lives in the Royal Navy, the two men refused and put their officer on the sledge and pulled him from one depot to next until Evans's health had deteriorated to the point that he would die without immediate medical attention. At that point, Crean volunteered to make a dash for help while Lashly agreed to stay with Evans, knowing that if Crean failed, Lashly would die with his officer. Despite having walked nearly 1400 miles by that time, Crean walked eighteen hours to reach the doctor and the dog team that went out and retrieved Evans, who lived. For their actions Evans and Lashly were given the highest award in the gift of the Crown for bravery in a civilian action, the Albert Medal.

Meanwhile Scott's party trudged southward, fearful that they would see in the distance some indication of Amundsen's party. One day, Bowers saw it: a black flag—they had been forestalled in their attempt to be the first persons at the last place on earth.

All provisioning was designed for parties of four and the addition of a fifth person complicated the process of cooking for Scott's team. Having failed to reach the pole before Amundsen, the party turned north without the sense of triumph they had hoped would accompany that part of the journey.

Theirs was a race with death. They retraced their steps across the polar plateau and back down the

Beardmore Glacier. By the time they reached the Great Ice Barrier (Ross Ice Shelf) Petty Officer Edgar Evans was showing signs of exhaustion and illness. Several severe falls into crevasses resulted in a concussion and he died in his sleep one night. The party was behind schedule, which meant that the inadequate food and fuel supplies (to heat meals and melt water) had to be stretched even more. By this time Captain Oates was suffering from severe frostbite, gangrene, and scurvy. Knowing his inability to maintain the pace needed for survival, in the middle of a whiteout storm when all safe movement outside the tent was impossible, he stood up—in great pain—and announced, "I'm going out now, and I may be some time." Oates walked to his death in the snow in the hope that, without him holding them up, his companions would survive.

The three men—Scott, Wilson, and Bowers—pitched their tent eleven miles from One Ton Depot confident that they could accomplish the short distance to the supplies the next day. But instead, a storm came up and lasted at least ten days. The three men died of exposure and starvation, complicated by scurvy.

Scott's last letters and final entries in his diary are the basis of fame that crowned his reputation in polar history. His last letter to Mrs. Wilson spoke of his affection for his friend and for the example of sacrifice Wilson had always maintained. In his final remarks to the public Scott noted:

> ...but for my own sake I do not regret this journey, which has shown that Englishmen can endure hardships, help one another, and meet death with as great a fortitude as ever in the past. We took risks, we knew we took them; things have come out against us, and therefore we have no cause for complaint, but how to the will of Providence, determined still to do our best to the last....Had we lived, I should have had a tale to tell of the hardihood, endurance, and courage of my companions which would have stirred the heart of every Englishman.

Over the past century, commentators have speculated as to the cause of the tragedy. All manner of explanations have been offered: taking the fifth man, using ponies, taking Petty Officer Evans instead of either Lashly or Crean, unlucky about weather condition. None of those issues would have resulted in the death of the final three men had Scott placed One Ton Depot where he planned to, instead of thirty miles farther north.

Ultimately why Scott died is not the issue. How he died matters most. Given his circumstances, his final notes are the highest expression of much of what Victorians believed about amateurism, courage, sacrifice, honor, and, above all, duty.

T. H. Baughman

See also **Amundsen, Roald; British Antarctic *(Terra Nova)* Expedition (1910–1913); British Antarctic *(Terra Nova)* Expendition, Northern party; British National Antarctic *(Discovery)* Expedition (1901–1904); Dogs and Sledging;History of Antarctic Science; Markham, Clements; Norwegian South Polar *(Fram)* Expedition (1910–1912); Oates, Lawrence Edward Grance; Ponies and Mules; Ross Ice Shelf; Ross Island; Royal Geographical Society and Antarctic Exploration; Royal Society and Antarctic Exploration and Science; Scurvy; Shackleton, Ernest; Wilson, Edward**

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SCOTTISH NATIONAL ANTARCTIC EXPEDITION (1902–1904)

On November 2, 1902, the Antarctic research ship SY *Scotia* sailed quietly down the lower Clyde from its berth in Troon, Ayrshire. There was no fuss nor fanfare, such as had accompanied the departure of Robert Falcon Scott's *Discovery* from the Thames a year earlier. This was the Scottish sabbath, and the expedition's leader, William Speirs Bruce, never courted publicity. The Scottish National Antarctic Expedition (SNAE) was inspired by Bruce: he was its progenitor, its organiser, and its leader, and its crew and its supporters were entirely Scottish. Bruce had been by rebuffed by Sir Clements Markham when he applied for a place on *Discovery,* and so was determined to prove that Scotland could raise an expedition for Antarctic research to rival the English. Markham accused him of "mischievous rivalry."

At that time, there were few in Britain who could match Bruce for his experience of the polar regions, and none who were so well qualified as a polar oceanographer. Endorsed by the eminent scientist Sir John Murray, and by both the Royal Scottish Geographical

Society and the Royal Society of Edinburgh, the expedition's principal aim was to carry out oceanographic research in high latitudes of the Southern Ocean, and thus to contribute to the general scientific surveys of Antarctica as proposed by Markham and Georg von Neumayer for the British National Antarctic Expedition and the German Antarctic expedition. The research would include systematic measurements of meteorology, biology, topography, and terrestrial physics, as well as deep-sea and other marine observations, and the aim was to land a wintering party, "for three years as near to the South Pole as possible." Although it became impossible to attempt to pioneer a route over the ice to the South Pole, all the other aims were successfully carried out.

Bruce purchased a former Norwegian Arctic whaler, *Hekla,* with the help of Colin Archer, the builder of Fridtjof Nansen's *Fram,* and had it converted at the Ailsa Shipbuilding Yards in Troon, and equipped with the latest marine engine, deep-sea dredges and trawls, and a fine laboratory. The total cost was £16,730, met chiefly though the munificence of the industrialists James and Andrew Coats of Paisley. The ship was barque-rigged, about 400 tons, length 140 feet (42.7 m), breadth 29 feet (8.8 m), and a drawing 15 feet (4.6 m) of water. It was well strengthened for working in ice and had a ship's complement of 35. The captain was Thomas Robertson, an experienced ice-master, and the crew, apart from Gilbert Kerr the piper, were all seasoned in Arctic whaling. The scientific staff, led by Bruce, included Robert Neal Rudmose Brown, botanist and zoologist; John H. Harvey-Pirie, medical doctor and geologist; Robert Cockburn Mossman, meteorologist; David Wilton, zoologist; and two junior members, Willie Cuthbertson, artist, and Alastair Ross, taxidermist. They were all recruited from amongst Bruce's friends in Scotland's academia.

Scotia met the first pack ice in latitude 60°28′ S on February 2, 1903, and steered a course for the South Orkney Islands, reaching them, for a brief landing, on February 4. They then pushed farther south, attaining 70°21′ S in the Weddell Sea on February 22. Not wishing to become icebound in an area where scientific work was limited, the expedition turned north and sailed to the South Orkney Islands, anchoring off Laurie Island on March 26. The expedition was frozen in and remained there until November 26, when *Scotia* left for Buenos Aires for re-victualling. On the second voyage Bruce came back to Laurie Island and then proceeded to 74° S, where he discovered new lands that he named "Coats Land," after his Scottish sponsors. He turned for home on March 31, 1904, reaching the Clyde to great acclamation on July 21.

The SNAE was the most successful of all those of the Heroic Age of polar exploration as regards its oceanographic work. In addition to a large quantity of data and specimens, a meteorological observatory, Omond House, was built on Laurie Island, which has since been transformed into the Argentine station Orcadas, as well as a magnetic observatory, Copeland House. One crew member, Allan Ramsay, died on the island of heart disease; otherwise the ship returned with everyone fit and well.

PETER SPEAK

See also **British National Antarctic *(Discovery)* Expedition (1901–1904); Bruce, William Speirs; German South Polar *(Gauss)* Expedition (1901–1903); History of Antarctic Science; Markham, Clements; Neumayer, Georg von; South Orkney Islands**

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SCURVY

Scurvy is caused by a deficiency of vitamin C, to be found in fresh fruit, vegetables, and uncooked or lightly cooked fresh meat. This disease was notorious during the eighteenth century and earlier for the toll it took on mariners making long exploring or trading voyages, such as George Anson's round-the-world voyage of 1740–1744. In contrast, James Cook's circumnavigation of the Antarctic continent of 1772–1775, amounting to 60,000 miles, resulted in the loss of very few men. Two decades earlier, the naval surgeon James Lind had written *A Treatise of the Scurvy* (1753) in which he indicated that fresh fruit, particularly oranges, would cure this ailment, although he did not have an accurate concept as why this was so. The Admiralty instructed Cook and his chief surgeon to carry out trials of a variety of such potential preventatives. In a letter to the president of the Royal Society after his return (1776), Cook set out

"The method taken for preserving the health of the crew of His Majesty's Ship Resolution during her late voyage round the world." He set great store on cleanliness and on "the inspissated juice of malt," on "Sour Kraut," and on "potable soup" ("the means of making the people eat a greater quantity of greens that they would have done otherwise") all supplied by the Admiralty, although he was unsure whether the pints of liquid malt would cure scurvy "in an advanced state at sea." But the true secret of Cook's success in the fight against scurvy was his gathering of fresh food at every anchorage. His editor and biographer, J. C. Beaglehole (1974: 704), wrote: "the sovereign thing was the unremitting insistence on fresh food," in addition to or in place of the barrels of salt beef and salt pork, "at every conceivable opportunity, fish, flesh and fowl—walrus, penguins—'scurvy grass' and every other variety of wild vegetables, the fruits and roots of the islands, the berries of Tierra del Fuego and the Arctic, a new batch of spruce beer—anything as long as it was fresh."

The influence of both Lind and Cook was strikingly demonstrated during the long years of Vancouver's circumnavigation (Watt et al. 1981: 51–71). The remedy for, if not the true cause of, scurvy was thus known by the end of the eighteenth century, so that the widespread incidence of the disease during the British Arctic Expedition of 1875–1876, commanded by Sir George Strong Nares, came as a considerable shock. The use of lime juice, rather than lemon juice, was discredited and ideas as to the cause of scurvy became chaotic (Savours and Deacon 1981).

The first expedition actually to winter (involuntarily) in the Antarctic was that of *Belgica,* commanded by Adrien de Gerlache, 1898–1899. Numerous digestive and other ailments affected both officers and men, but scurvy (called "polar anaemia") seems to have been kept at bay by the killing and eating of penguins and seals, advocated by the surgeon Frederick A. Cook. "If you want there is always enough food," wrote mate Roald Amundsen after the doctor's shooting of a Ross seal on the pack ice (Decleir 1999: 170).

The interior of mainland Antarctica remained virtually unexplored until extensive sledging journeys were made in various directions from *Discovery* during the British National Antarctic Expedition (1901–1904) under Robert Falcon Scott, followed by others made by personnel from Ernest Shackleton's British Antarctic Expedition, Douglas Mawson's Australasian Antarctic Expedition, and Scott's last expedition. The sledging diet of these parties largely lacked fresh food. For example, that of Scott's polar party of 1911–1912 consisted of pemmican (dried meat pounded with fat), biscuits, butter, cocoa, sugar, and tea, plus a small amount of pony meat, the rest of the meat being fed to the dogs (Rogers 1981). Scott, Edward Wilson, and particularly Shackleton returned from the southern journey of 1902–1903 after 92 days away from *Discovery* suffering from moderately advanced scurvy. Neither of Shackleton's main parties—heading for the South Pole and the South Magnetic Pole—suffered from scurvy, to a great extent because, at the recommendation of Dr. Eric Marshall, they were "primed" with a diet heavy in fresh meat for a period before leaving base. The expedition members wintering at Hut Point, Cape Royds, and Cape Evans were able generally speaking to keep scurvy at bay (or to eradicate it in *Discovery*) by killing seals and birds.

The true cause of scurvy, the lack of ascorbic acid from the diet, was unknown during these pioneering British expeditions. One of the theories as to its cause advocated the existence of "ptomaines" in tinned meat, a hypothesis supported by Reginald Koettliz, senior surgeon in *Discovery,* who, with Wilson, opened and examined every tin before use. When an outbreak of scurvy took place on board ship, second-in-command Albert Armitage and then Scott ordered the serving of fresh seal meat to alleviate the problem, which it did.

The absence of scurvy during the dash to the South Pole and back made by Amundsen and his companions in 1911–1912, using dog teams for transport, can be attributed to the explorer's foresight in his plan to kill a number of the dogs in order not only to feed the other dogs but to provide fresh meat to the five men in the party, as well as to the speed with which the party reached the Pole and returned.

The last expedition of the "Heroic Age" to make long sledge journeys into the interior of the continent was Shackleton's Ross Sea Party. Its members were required to lay depots as far as the Beardmore Glacier to be picked up by the trans-Antarctic party from the Weddell Sea. All six of the advanced party were severely afflicted with scurvy during a very long sledging season—more than six months—one man (A. P. Spencer-Smith) dying. The main party of Shackleton's Imperial Trans-Antarctic Expedition survived the loss of *Endurance* by subsisting largely on seal and penguin meat during the following 10 months. In fact, by 1914 it was generally recognised that scurvy was a deficiency disease, and Shackleton took advantage of the new ideas as regards preparations for the crossing by taking capsules of lime juice to be used on sledge journeys and added dried milk to the sledging ration. However, with the loss of the ship, these measures were wasted.

With the growing understanding of vitamins between the World Wars, scurvy in the Antarctic was eliminated.

Ann Savours

See also **Amundsen, Roald; Australasian Antarctic Expedition (1911–1914); Belgian Antarctic *(Belgica)* Expedition (1897–1899); British Antarctic *(Nimrod)* Expedition (1907–1909); British Antarctic *(Terra Nova)* Expedition (1910–1913); British National Antarctic *(Discovery)* Expedition (1901–1904); Cook, James; Imperial Trans-Antarctic Expedition (1914–1917); Ross Sea Party, Imperial Trans-Antarctic Expedition (1914–1917); Scott, Robert Falcon; Shackleton, Ernest; Wilson, Edward**

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SEA ICE: CRYSTAL TEXTURE AND MICROSTRUCTURE

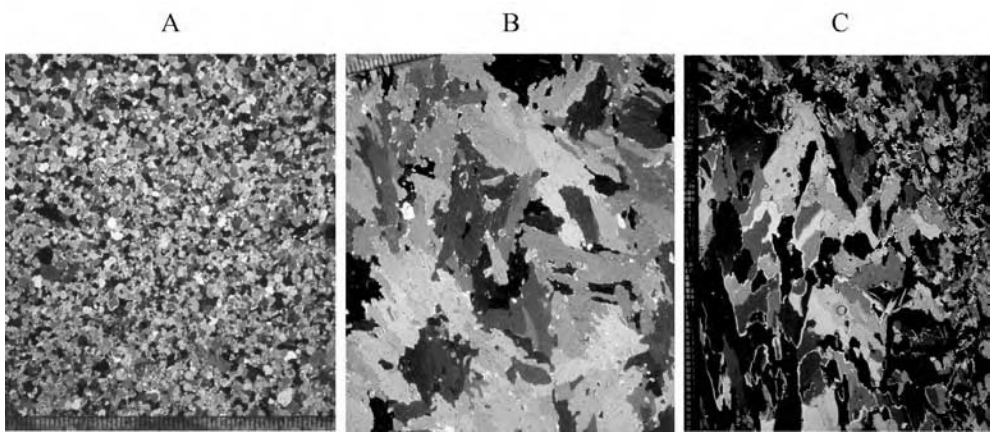
Introduction

The importance of the polar oceans' sea ice cover for global climate and polar ecology derives in significant part from the manner in which ice grows from seawater. Thus, sea ice contains large numbers of brine pockets, salt particles, and other inclusions, typically ranging from few micrometers to several centimeters in size. The size, morphology and distribution of these inclusions and the surrounding ice crystal matrix is referred to as the texture or microstructure of the material. The remarkable properties of sea ice, such as its high albedo (ability to reflect light) or its role as a habitat to microorganisms thriving within the pore space, are determined in large part by its texture and microstructure.

The microstructure of a sea-ice sample also contains a record of ice growth conditions, and researchers have made use of this fact to learn more about the complex evolution of the ice cover. Such studies, employing a wide range of methods, from the traditional approach of cutting sections out of ice cores drilled in the field to nondestructive use of magnetic resonance imaging, can also offer more general insights into the formation and evolution of rocks and industrial materials at temperatures close to the melting point.

Major Ice Textures

In the Antarctic, four principal modes of sea-ice growth and formation can be distinguished. The different ice-growth processes result in different morphologies and spatial arrangements of ice crystals (or ice grains), air and brine pockets and other inclusions. Typically, ice crystals are several millimeters to >10 cm in size and the term *texture* is used here in accordance with the glaciological literature (Shumskii 1964; Weeks and Ackley 1986) to denote the size, shape and orientation of these crystals. The distribution of liquid and solid inclusions within the ice matrix as well as the morphology and substructure of individual crystals is denoted as the ice or pore *microstructure*. Note, that while modern geological literature tends to use the terms texture and microstructure synonymously (Passchier and Trouw 1996), in the materials science field (and in some foreign languages, such as German or French) the terms may have different meanings. In describing and classifying different ice types based on crystal or pore attributes, it helps to distinguish between textural classifications that are purely descriptive of ice crystal texture (and possibly microstructure) and genetic classification schemes that distinguish between different formation modes as deduced from a number of different observations, including but not limited to the ice texture and microstructure.



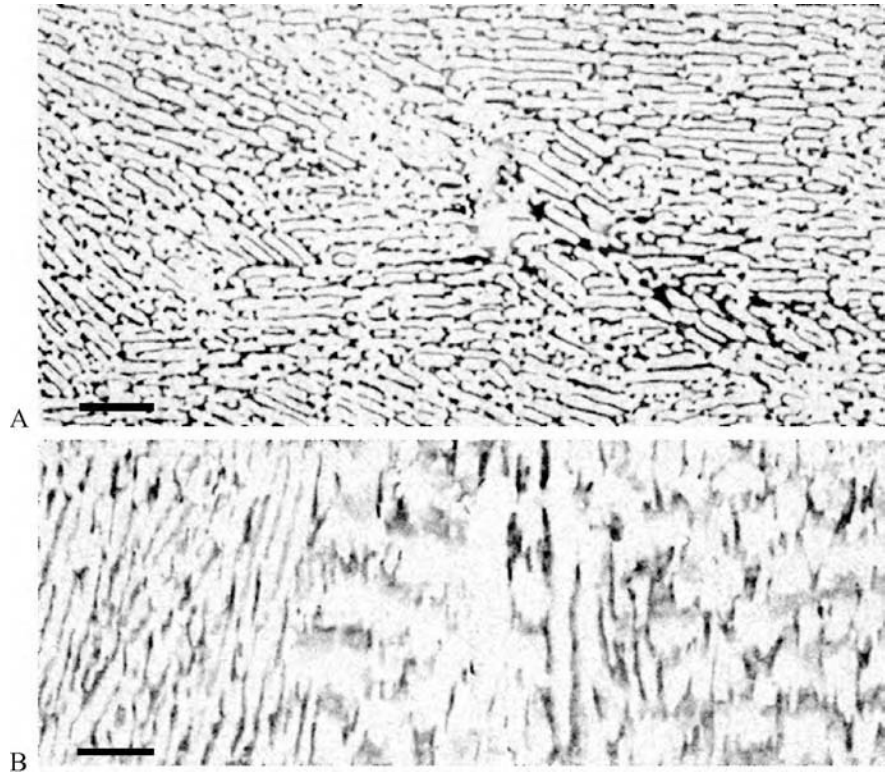
Thin sections of orbicular granular sea ice formed from frazil ice (A, horizontal section), columnar sea ice grown through congelation of seawater at the base of the ice cover (B, horizontal section), and mixed columnar/granular sea ice formed through consolidation of a mesh of ice platelets accumulating underneath the ice cover (C, vertical section). Samples were obtained in first-year sea ice in the Weddell Sea, Antarctica, and were photographed between crossed polarizers, rendering individual crystals in different colors.

During the onset of ice formation in open water, along the advancing marginal ice zone and within leads or polynyas, wind-mixing typically results in the formation of frazil ice. Frazil crystals are mm- to cm-sized spicules or platelets of ice, not unlike a submarine type of snow, often aggregating into flocs as they collide in the uppermost meters of the water column. Eventually, the crystals accumulate at the ocean's surface and through further growth and deformation form grease or pancake ice. The rate of ice growth in the water column is typically limited by the rate at which the latent heat of fusion that is released during the freezing of seawater can be transferred to a heat sink, either the cold atmosphere or the supercooled ocean (i.e., at a temperature below the freezing point, typically at –1.9°C). Frazil ice formation is typically associated with the highest rates of heat transfer. Hence, an unconsolidated, highly porous frazil layer of several decimeters thickness can easily be formed within a few hours under cold, windy conditions.

Once this surface grease ice layer dampens mixing in the water column to the extent that no further frazil formation is possible, it consolidates through freezing of seawater in the interstices between crystals. During this consolidation, salt is expelled from the ice. This expulsion is mostly driven by convective exchange, with dense, saline, cold brine overlying less dense, fresher and warmer brine, and to a lesser extent volume expansion of water during the freezing process. The ice formed through consolidation of frazil typically consists of isometric, small (few millimeters across) grains and is referred to as granular ice. Individual grains are typically rounded (orbicular granular) and contain few if any inclusions. Brine is confined to the interstitial pore space. Due to the dynamic ice-growth environment of the Southern Ocean, granular ice of frazil origin is the most common type of ice found in the Antarctic, accounting for more than half of the total ice volume (Eicken 1998; Jeffries et al. 1994; Lange and Eicken 1991; Weeks and Ackley 1986; Worby and Massom 1995).

The quiescent accretion of sea ice at the bottom of an existing ice cover results in the formation of vertically elongated (prismatic) crystals, typically several centimeters in diameter and more than 10 cm long. This type of ice is referred to as columnar ice, or, based on its mode of formation, congelation ice. The downward growth of a floating sea-ice sheet is very similar to the growth of ordinary lake ice, and this is reflected in similar grain textures. Columnar sea-ice crystals, however, contain numerous layered brine inclusions, with seawater and brine trapped between ice lamellae protruding downward from the base of the ice sheet. Vertically oriented ice lamellae possess a downward growth advantage, potentially enhanced by steady currents under the ice. This favours the growth of ice crystals composed of vertically oriented lamellae that are aligned within the horizontal plane if under-ice currents are consistently unidirectional.

In the Arctic, such strongly aligned columnar ice is the dominant ice textural type and accounts for roughly two thirds to three quarters of the total ice volume. Dynamic growth conditions in the Antarctic limit the occurrence of columnar ice to the lowermost layers of the ice cover, the landfast ice belt along the coast and within leads and polynyas that freeze over during calm conditions (wind speeds typically less than 5 to 10 m s^{-1}, Eicken and Lange 1989; Smith et al. 1990). Furthermore, while vertically oriented columnar crystals are common, horizontal alignment



Pore microstructure of artificially grown columnar sea ice obtained through magnetic resonance imaging. Shown are a horizontal (A) and a vertical (B) section, with very distinct brine layers (appearing dark) surrounding individual ice lamellae (appearing bright) within each crystal. Cylindrical brine tubes or channels can also be discerned in the central part of both A and B. Note how brine layers mimic grain textures apparent in parts B and C of the previous figure.

is observedly only infrequently and generally both horizontal and vertical dimensions of columnar crystals in Antarctic sea ice are smaller than their Arctic counterparts.

The formation of so-called platelet ice, common along the margins of the Antarctic ice shelves where it can account for up to half of the ice volume, is similar in many ways to that of frazil ice. Thus, platelet ice results from the accumulation of large (several centimeters diameter), platy ice crystals in layers decimeters to on occasion meters thickness underneath the ice cover. Due to the larger size of voids enclosed by the platelets, the shapes and sizes of individual crystals within consolidated platelet ice span the range from granular to columnar ice (mixed columnar/granular ice).

Underwater ice platelets form during the ascent of supercooled water masses that have come into contact with the base of the floating ice shelves (Lewis and Perkin 1986). The freezing point of seawater is both salinity and pressure dependent (approximately –1.92°C at the surface for seawater of salinity 35, and –2.00°C at 1000 m depth). As water circulates underneath an ice shelf it initially melts back the ice shelf base in deeper water, eventually cooling to the freezing point at depth. As the water rises along the sloping ice-shelf base, the pressure drops and supercooling with eventual ice formation sets in. Ice crystals grown under these conditions in the water column tend to be much larger (hand-sized plates have been found) than ordinary frazil ice and accumulate in thick layers underneath landfast and drifting sea ice in front of the ice shelves (Eicken and Lange 1989; Smith et al. 2001). In some locations, such as McMurdo Sound, the supercooled water can make it all the way to the ocean surface without ice crystal formation, leading to direct accretion of platelet ice onto the existing ice cover.

The Antarctic sea-ice zone receives substantial snowfall, with low pressure weather systems transferring moisture from the surrounding ocean areas. In some regions it is possible to accumulate as much as 1 to 2 m of snow on the sea ice. The ice surface is depressed below sealevel as a result of snow loading. If the underlying layers are sufficiently permeable (with pathways provided by brine channels or cracks), the ice surface and snow base floods and eventually refreezes. The snow ice formed in this fashion is composed of a mixture of frozen seawater, brine and snow crystals. Texturally, it is often difficult to distinguish from granular ice of frazil origin. On occasion, ice grains in snow ice exhibit polygonal outlines in thin sections and are then referred to as polygonal granular ice.

Superimposed ice, formed from snow meltwater that percolates downward and refreezes at the cold ice surface in late spring and early summer, is also typically of polygonal granular texture (Kawamura et al. 1997, 2004). The contribution of snow to the mass budget of Antarctic sea ice can be significant; in some areas as much as half of the total ice mass can be composed of snow ice (Jeffries et al. 1994, 2001; Kawamura et al. 1997, 2004). In all but the most extreme cases (i.e., snow accumulation rates of several meters per year) the net effect of snow deposition on sea ice is a reduction in total ice volume due to its small thermal conductivity which is lower than that of sea ice by one order of magnitude. However, snow-ice and superimposed-ice formation help to significantly offset this reduction in ice mass from snow deposition. While large-scale modeling has made significant progress in simulating snow ice formation (Fichefet and Morales Maqueda 1999; Wu et al. 1999), analysis of sea-ice cores (textural analysis and stable-isotope measurements) is the only means of directly determining the contribution of snow to the ice mass budget.

Pore Microstructure

The ice crystal lattice structure does not allow for substantial incorporation of the major sea salt ions into the solid ice. Instead, salt is rejected and builds up ahead of the advancing ice-water interface during ice growth. Typically between 60% and 85% of the total amount of salt is expelled completely from the growing ice in the form of cold dense brines. The remainder is trapped between and within the crystals. Salt buildup ahead of the ice-water interface is ultimately responsible for the development of parallel rows of ice blades (ice lamellae) that protrude from the bottom of growing columnar ice. Differences in the rate of salt and heat transport at the millimeter-scale result in a thin layer of supercooled water just below the ice. This supercooled water in turn fosters the establishment of a corrugated ice bottom where the ice lamellae shoot down into the supercooled layer and part of the brine remains trapped between the lamellae.

Traces of these ice blades and the interspersed brine layers can be discerned in a thin section photograph. An image obtained with the aid of magnetic resonance imaging (MRI) can provide a close-up view of parallel arrays of inclusions within individual crystals. Along the boundaries of crystals with differently oriented inclusion arrays, slightly larger, cylindrical brine tubes are apparent. These tubes merge into systems of interconnected channels that can reach several centimeters in diameter and more than a meter in length.

Gas inclusions typically only account for a small fraction of the total volume of foreign inclusions in sea ice. Frazil ice formed in a turbulent upper ocean can trap air bubbles in the ice. Gas or vapour inclusions can also appear in brine channels as a result of temperature changes and displacement of dissolved gases from the growing ice (Light et al. 2003). Solid salts precipitate as the temperature of growing sea ice decreases, with the two most prominent salts, mirabilite ($NaSO_4 \times 10\ H_2O$) and hydrohalite ($NaCl \times 2\ H_2O$) starting to precipitate as the temperature drops below approximately –6°C and –22°C, respectively (Marion and Farren 1999).

Methods of Studying Sea Ice Microstructure

In principle, the methods employed in obtaining samples and analysing sea-ice microstructure and properties are very similar to those employed by glacier geophysicists studying ice cores drilled deep into the Antarctic ice. Ice cores are typically drilled with a fiberglass-barrel, motor-powered coring system. With the use of extension rods, such corers can penetrate between 5 and 10 m of ice. In order to prevent loss of brine from the porous ice, cores are typically precut at the sampling site after photographing and temperature measurements, and then transferred to storage at temperatures of below –20°C to prevent loss of brine. A standard variable determined on most cores in addition to temperature is the ice bulk salinity, which involves melting of the sample and subsequent electrolytical conductivity measurements. Other biogeochemical and stable-isotope measurements are typically also carried out on melted core sections.

The standard approach to textural and microstructural analysis involves the preparation of thin sections that can be examined with magnifying lenses or under the microscope in both ordinary and polarized light. Slices sawed off the core are frozen onto glass slides and subsequently thinned to few tenths of a millimeter in thickness. Placed between crossed polarizing sheets, these thin sections exhibit interference colors that indicate the shape and crystallographic orientation of individual ice crystals. The pore morphology can be studied at higher magnification in ordinary transmitted light. Since samples are typically prepared at low temperatures to avoid brine loss and alteration during processing, the pore microstructure is artificially changed as pores shrink and salts precipitate during the cooling process. This creates the dilemma that in order to insure overall sample integrity, standard core analysis is completed at artificially low temperatures, significantly altering pore microstructure.

Many processes of scientific interest occur at higher temperatures, however. This has led to alternative approaches in studying ice microstructure, including x-ray computed tomography (CT; Kawamura 1988) or magnetic resonance imaging (MRI; Eicken et al. 2000; Menzel et al. 2000). These methods derive their power from the fact that samples can be studied nondestructively by determining density contrasts (x-ray CT) or can distinguish between water molecules part of the solid ice or liquid brine (MRI). Furthermore, experiments conducted in closed sample vessels allow analyses of the thermal evolution of pore microstructure. The most advanced approach to the problems posed by thermal alterations of sea ice after sampling has been taken by a group in New Zealand who have pioneered *in situ* studies of brine volume and mobility of liquid water in sea ice using magnetic resonance techniques that rely on the Earth's magnetic field (Callaghan et al. 1999).

Microstructure and Salt Distribution and Their Impact on Ice Properties and Ice Ecology

The transport of energy and matter through sea ice is controlled by its texture and microstructure. This derives largely from the contrasting physical properties of ice (poor electrical conductor, good thermal conductor, mechanically strong) and brine (excellent electrical conductor, poor thermal conductor—although brine movement can under certain conditions enhance thermal transport—and mechanically weak). The volume fraction of brine, the number density, morphology (tubular versus layered), and connectivity of brine inclusions are of particular importance in this regard. While the growth mechanism and growth rate as well as the grain texture determine the bulk salinity, spatial arrangement of pores, their volume fraction, micromorphology and connectivity are mostly controlled by temperature. With decreasing temperatures, pores shrink and brine tubes or layers segregate into individual, disjoint pores as part of the liquid freezes out, leaving behind a colder, more saline brine. This segregation and reduction in connectivity of pores greatly reduces the ice permeability, which in turn significantly reduces fluid flow through the ice. Cold horizons of lower salinity, typically found just below the ice surface, can hence become effectively impermeable. This can prevent surface flooding in cold ice that is submerged below sea level by deep snow cover. Once the ice interior and surface warm, however, ice permeability goes up and seawater and brine are free to percolate upward, resulting in formation of snow ice (Maksym and Jeffries 2000). Such flooding processes explain higher salinities found in the lower layers of the snow cover. High surface sea-ice salinities are due to both potential flooding and higher retention of salts in the upper portions of the ice cover, which experienced more rapid growth rates. Surface flooding is also of importance because it can supply large amounts of nutrients, allowing microalgae, which are prolific throughout the ice cover, to thrive in the uppermost layers where they are protected from grazers in the water column (Fritsen et al. 1998).

Texture and microstructure figure prominently in the role of sea ice as a habitat for a wide range of microorganisms. Algae attached to the ice bottom or residing within pores in the ice interior are provided with a stable platform for growth, while the size spectrum of the pore space serves to exclude larger grazing organisms (Krembs et al. 2000). Granular ice often contains much larger numbers of microorganisms since frazil-ice formation and aggregation represents a natural concentration mechanism (Thomas and Dieckmann 2003). Pore microstructure and the extreme brine salinities within individual pores are also of interest as analogs of potential extraterrestrial ice habitats (Thomas and Dieckmann 2002).

HAJO EICKEN

See also **Exobiology; Ice Core Analysis and Dating Techniques; Isotopes in Ice; Marginal Ice Zone; Pack Ice and Fast Ice; Polynyas and Leads in the Southern Ocean; Precipitation; Sea Ice: Microbial Communities and Primary Production; Sea Ice: Types and Formation; Surface Energy Balance; Thermohaline and Wind-Driven Circulations in the Southern Ocean**

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SEA ICE: MICROBIAL COMMUNITIES AND PRIMARY PRODUCTION

Sea Ice as a Habitat

Antarctic sea ice cover undergoes a dramatic seasonal expansion from a minimum of approximately 4 million km^2 of mostly multiyear pack ice in the austral summer to 19 million km^2 of mostly first-year pack ice in the winter. In the early stages of pack ice formation, dense concentrations of frazil ice develop rapidly under turbulent conditions as large quantities of heat are extracted from the surface ocean. As the sea surface calms, the frazil ice crystals float to the surface where they coalesce into semiconsolidated grease ice, and eventually, into thicker nilas and pancake ice. Additional freezing and horizontal movement fuses ice pancakes together to form a continuous ice pack; that is, the pack ice. Subsequent ice thickening beyond the consolidated pancake stage proceeds vertically downward as heat is extracted from the sea ice surface by the cold atmosphere. This new layer of ice is called congelation ice and is the primary component of land-fast ice, which does not have an initial frazil ice stage. The lowermost layer of the growing congelation ice, the skeletal layer at the ice–water interface, is highly porous with a temperature just below the freezing point of seawater. Rafting of ice floes as pack ice is moved by the wind and tides causes breakage and occasionally forces parts of the floe underwater, thereby flooding the ice surface with seawater. Similarly, heavy snow cover can also result in depression of the ice floe below the sea surface and flooding at the ice surface.

Platelet ice, a semiconsolidated layer of ice ranging from a few centimeters to several meters in thickness, is commonly observed beneath sea ice in regions adjacent to floating ice shelves. Platelet ice is the most porous of all sea ice types, being composed of approximately 20% ice and 80% seawater by volume. Although the extent of platelet ice habitats is not known, 45% of the continental margin in the Antarctic is associated with an ice shelf, suggesting this habitat may be relatively common. Platelet ice provides approximately five times more surface area for attachment of algae than the skeletal layer where most of the biomass within the congelation ice is concentrated. The platelet ice layer is also characterized by relatively rapid nutrient exchange; in contrast to much of the congelation ice, where physical nutrient replenishment is controlled by convection and brine drainage, the rate of nutrient exchange within platelet ice covaries with tidal height and sub-ice currents.

Sea Ice Microalgae

Frazil ice formation generally begins in the autumn when there are still substantial microbial populations left over in surface waters from the preceding spring blooms. As a result, organisms such as microalgae, protists, and bacteria are often scavenged from the water column as the newly formed frazil ice crystals rise to the surface. These organisms, especially diatoms, flourish within the distinct microhabitats which are created when sea ice forms and ages. The primary advantage afforded by sea ice is that it provides a platform from which sea ice algae can remain suspended in the upper ocean where light is sufficient for growth (except for areas where snow cover is extremely thick). However, sea ice habitats are often characterized by steep gradients in temperature, salinity, light, and nutrient concentration. Consequently, the greatest fraction of sea ice microalgae often reside in the bottom 20 cm of the ice sheet where environmental conditions are generally stable and more favorable for algal growth. Bottom ice communities that form in the skeletal layer can extend as far as 0.2 m up into the ice, their upward distribution generally being limited by nutrient availability and high brine salinity within the sea ice interior. Here, algal biomass has been observed to exceed 200 mg Chl *a* m^{-2}, a value comparable to a productive water column yet contained within a much smaller volume.

Surface microbial communities form in regions of the pack that become flooded with nutrient-rich seawater, due to ice rafting or snow loading. Such surface flooding occurs over 15%–30% of the ice pack in Antarctica and the communities that live there can attain levels of algal biomass ranging from 80 to 244 mg Chl *a* m^{-2}.

Under certain conditions, microalgae may also be found in internal layers, where they are often subjected to large environmental fluctuations. For example, brines with salinities as high as 173 psu and temperatures as low as –16°C have been measured in the topmost layers of sea ice, high enough to inhibit growth of most sea ice algae. In addition, increasing temperatures in the late spring may result in flushing of relatively fresh meltwater through the ice sheet, exposing microalgae to a lower salinity environment. Internal communities are generally located within a frazil ice layer or where seawater can infiltrate the ice floe. These communities are seeded by the particles scavenged during frazil ice formation and are especially dependent upon nutrient availability. The highest biomass accumulation recorded for internal communities is 50 mg Chl *a* m^{-2}, with most ranging from 0.5–30 mg Chl *a* m^{-2}.

Platelet ice, with its high surface area and high porosity, harbors some of the highest accumulations of sea ice algae found either in Antarctica or the Arctic, occasionally exceeding 1000 mg Chl *a* m^{-2}.

Other Sea Ice Biota

Sea ice algae sustain a wide variety of organisms, especially during the winter months when other sources of food are lacking. Because sea ice microalgae produce large amounts of dissolved and particulate organic matter, bacteria and fungi live in close proximity to the primary producers, as do viruses, which can be highly enriched in Antarctic sea ice. A wide array of single-celled protists, including ciliates, flagellates, and especially foraminifera, are components of the sea ice microbial community. Larger organisms residing in sea ice include flatworms and harpacticoid, calanoid, and cyclopoid copepods. At the ice-water boundary, even larger organisms such as fish (mainly *Pagothenia borchgrevinki*), amphipods, and euphausiids dominate along with other copepod species that are not found within the ice. Those organisms recorded from within the ice are evidently feeding directly on bacteria, protists, and algae within the brine channel system, although the size of the channels effectively limits how much of the ice these grazers are able to exploit. Organisms living below the ice feed on algae and bacteria covering the peripheries of ice floe surfaces, but also on the flux of particulate material being released from the ice.

The extent and persistence of sea ice has been linked to krill *(Euphausia superba)* recruitment and spawning. Although adult krill can withstand periods of starvation, juvenile krill cannot; therefore, the food contained within sea ice is vital to their winter survival. In winter, approximately three times more krill can be found under sea ice than in adjacent open waters, with the majority of the krill being found in a band between 1 and 13 km inside the sea ice edge (the boundary between open ocean and pack ice). During years of heavy sea ice or late melting of the pack ice in spring, krill spawn earlier in the season and reproduction rates are relatively high. In contrast, after winters with reduced ice extent and duration, krill reproduction is low. It is evident that extended sea ice cover fosters increased krill.

Methods for Estimating Primary Production in Sea Ice

Algal Biomass Accumulation

Early estimates of primary production in sea ice were based on the accumulation of algal biomass, generally either Chl *a* or particulate organic carbon, during the growing season. To derive an estimate of production in this way, a station would be sampled repeatedly over time and changes in algal biomass noted. This technique is well suited to the sea ice habitat because sea ice microalgae are anchored to the ice substrate and, therefore, the same population can be sampled repeatedly. In other marine systems, such as the open ocean, currents continually move algal populations around, making repeated sampling of the same population difficult.

However, estimating primary production on the basis of accumulating algal biomass is not without its drawbacks. Primary production derived from changes in standing crop are, by definition, net primary production estimates, which are necessarily smaller than gross primary production. This is because losses of material due to respiration are not accounted for. Neither is grazing, which also can result in the loss of algal biomass. Where these losses are important, biomass accumulation may severely underestimate gross primary production. Estimating production via changes in algal biomass accumulation is still of value, however, because it is a simple, direct measurement that does not require invasive techniques and yet yields a reliable minimum estimate for primary production.

Photosynthesis Versus Irradiance (PE) Determinations

One of the most widely used methods for estimating primary production in sea ice (and in the water column) is to collect ice algae from the field, bring them into the laboratory and measure, via incorporation of radiolabelled carbon (^{14}C, carbon-14), the maximum photosynthetic rate (P^*_m), and the photosynthetic efficiency (α^*) as a function of light intensity. When these photosynthetic parameters are combined with light measurements from the field, primary production can be estimated. Generally, sea ice microalgae and the associated microbial community are collected from sea ice by removing an intact core sample. Algae are removed from the sea ice matrix by scraping or by melting the core in a darkened bottle to which an appropriate quantity of 0.2 μm filtered seawater has been added to reduce osmotic shock.

A significant problem with estimating primary productivity in sea ice using this approach is that the spectral quality of the light source used to estimate P^*_m and α^* is often very different from that within the original, undisturbed sea ice. Incubation light sources are usually weighted towards the red end of the visible spectrum, while the natural light within the ice is dominated by blue or green wavelengths. Even though the amount of light measured under both circumstances may be equal, photosynthetic pigments produced by the algae are much more efficient at absorbing blue light than red light. As a result, the value derived for α^* (P^*_m is insensitive to spectral quality) is often underestimated during PE determinations.

One way to compensate for this effect is to apply a spectral filter to the light source used during the incubations so that it mimics the light field the algae would be exposed to in the ice. Although this correction is simple to implement, it cannot completely account for the fact that the spectral light distribution changes with depth within the ice. Above the algal layer, it is dominated by the blue wavelengths that are readily absorbed by algal pigments. Further down, however, selective absorption of the blue wavelengths by algae results in a spectral light distribution that is dominated by green light. In this case, the value of α^* derived during PE determinations will be greater than that actually expressed by algae in undisturbed ice and productivity will be overestimated accordingly. This correction works best under conditions where algal biomass is low and hence the spectral distribution of the incident light is not changing rapidly with depth within the algal layer. In this case, the α^* will be more appropriate to all depths within the algal layer, and not just those near the surface.

Oxygen Microelectrodes

Ideally, scientists would directly measure primary productivity in the original sea ice, without disrupting the sea ice habitat. New developments are coming closer to this ideal, although it has not yet been attained. Oxygen (O_2) microelectrodes are now used to measure the photosynthetic rates of ice algae in virtually intact cores, without seriously disrupting the algal community. With this approach, the lowermost 0.2 m of an ice core is placed bottom-up in a temperature-controlled water bath. The core is illuminated from below and O_2 concentration is measured across the diffusive boundary layer using an O_2 microprobe. By repeating the experiments at a variety of light intensities, and by using dark controls to correct for respiration, PE relationships can be evaluated just as they are using the ^{14}C approach.

There are a number of shortcomings to this method, however. First, the act of inserting the sampling apparatus through the diffusive boundary layer reduces the thickness of that layer by 25%–45%, thereby altering the actual O_2 flux. Fortunately, this effect is minimized where O_2 gradients are small and when there is no fluid flow around the tip of the O_2 probe. Given these caveats, this method is likely to be accurate to within ±20%. Finally, this method is only effective at measuring productivity in bottom ice communities. Internal, surface, and platelet ice communities have diffusion paths that are too long to evaluate O_2 diffusion reliably. However, considering that the majority of algal biomass in the Antarctic is found in the bottom layers of the congelation ice, this method is likely to prove valuable in the future.

In Situ ^{14}C Incorporation

An incubation technique has been developed recently to measure primary production in place in a wider variety of sea ice habitats. The concept behind this method is that an ice core can be extracted from congelation ice and cut into 1-cm slices which are placed into individual petri dishes for inoculation with ^{14}C bicarbonate. These petri dishes are then stacked in the order they were collected, placed in an acrylic-glass barrel, and returned to their original position in the ice floe where they are incubated. This method provides fine-scale resolution of primary productivity throughout the ice column without severe disruption of the sea ice structure and light field.

The primary advantage of this approach is that the algae are incubated under as natural a light field as possible, eliminating the need to correct for spectral light quality. In addition, because the algae are incubated in place, they are exposed to the same vertical gradients in temperature and brine salinity as undisturbed populations, resulting in more realistic productivity estimates. The major drawback to this technique is the disruption of the ambient nutrient field. Brine tubes and channels act as conduits in intact sea ice, providing nutrients to the upper layers that are not in intimate contact with underlying seawater. Severing these conduits by sectioning the core could alter the nutrient field and result in unrealistic rates of primary production. Under conditions where nutrient concentrations are not limiting, this method is likely to yield estimates of primary production that are superior to most other methods.

Numerical Modeling

One of the more complex methods for determining, and understanding, primary production in sea ice is through numerical modeling of the sea ice system. This complex technique requires a thorough knowledge of both the physics and biology of the sea ice system, and to date has been applied relatively infrequently. Nevertheless, using such numerical models, the complete annual cycle of primary production across the entire Antarctic can be simulated as a function of temperature, salinity, nutrient, and light availability to gain a better understanding of the processes controlling algal distributions in sea ice as well rates of primary production.

Estimates of Algal Production

Curiously, the two minimally invasive *in situ* techniques described above came to very different conclusions concerning the accuracy of standard ^{14}C incubation techniques used most often for estimating primary production in sea ice. Estimates of photosynthetic carbon fixation made using microelectrodes to measure diffusion of oxygen through the boundary layer were very low, with hourly production rates of 0–1.78 mg C m^{-2} hr^{-1}. These estimates are on the low end for Antarctic sea ice, particularly in the spring when rates are generally the highest. Because this technique is the least invasive of all known methods for estimating sea ice primary production, the low values obtained by this technique has led the developers to speculate that previous estimates of sea ice production may be too high. In contrast, the ^{14}C technique showed that production within the sea ice interior was much higher than previously reported and that estimates of primary production based on bottom ice communities were likely underestimates. Clearly, additional data need to be collected to evaluate the relative ability of these two approaches to estimate sea ice primary productivity.

Estimates of annual sea ice primary production from direct ^{14}C uptake rate measurements indicate that annual production in the Antarctic ranges from 5–15 g C m^{-2} yr^{-1} (grams of carbon per square meter per year). This range is consistent with biomass accumulation data which give a range of 0.04–20 g C m^{-2} yr^{-1} for Antarctic congelation ice, a value that increases to 0.04–44 g C m^{-2} yr^{-1} in regions with a platelet ice layer. Despite the small sample sizes, it is still probably fair to conclude that even in the most productive habitats, annual production in sea ice is below 50 g C m^{-2} yr^{-1}, an amount similar in magnitude to the least productive regions of the open oceans.

Annual primary production integrated over the entire Antarctic region is calculated to range from 30–70 Tg C (Tera grams of carbon). Total primary production is a function of both the sea ice extent and the rate of primary production per unit surface area and has an error associated with it of ±30%. Primary production in Antarctic sea ice is greatest in November (13 Tg C $month^{-1}$, or Tera grams of carbon per month) as spatially integrated rates of production increase by a factor of four and sea ice coverage remains high. Annually, over 90% of the algal growth takes place within first-year sea ice and approximately 60% takes place during November and December. Antarctic-wide production declines between December and April, due to the dramatic decrease in sea ice coverage. The production rate per unit area peaks in January in both first-year (2.2 g C m^{-2} $month^{-1}$) and multiyear sea ice (1.1 g C m^{-2} $month^{-1}$).

The production rate of 30–70 Tg C yr^{-1} for Antarctic sea ice is about 1%–2% of the annual primary production in the Southern Ocean. However, sea ice primary production is a much larger fraction (10%–28%) of total production in the ice covered waters of the Southern Ocean, which ranges from 141 to 383 Tg C $year^{-1}$ and includes the highly productive marginal ice zones. Therefore, in those waters that are ice covered for part of the year, algae growing within sea ice are an important component of the marine food web.

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See also **Algae; Biodiversity, Marine; Carbon Cycle; Copepods; Fish: Overview; Food Web, Marine; Marginal Ice Zone; Pack Ice and Fast Ice; Phytoplankton; Productivity and Biomass; Sea Ice: Crystal Texture and Microstructure; Sea Ice: Types and Formation; Toothfish; Zooplankton and Krill**

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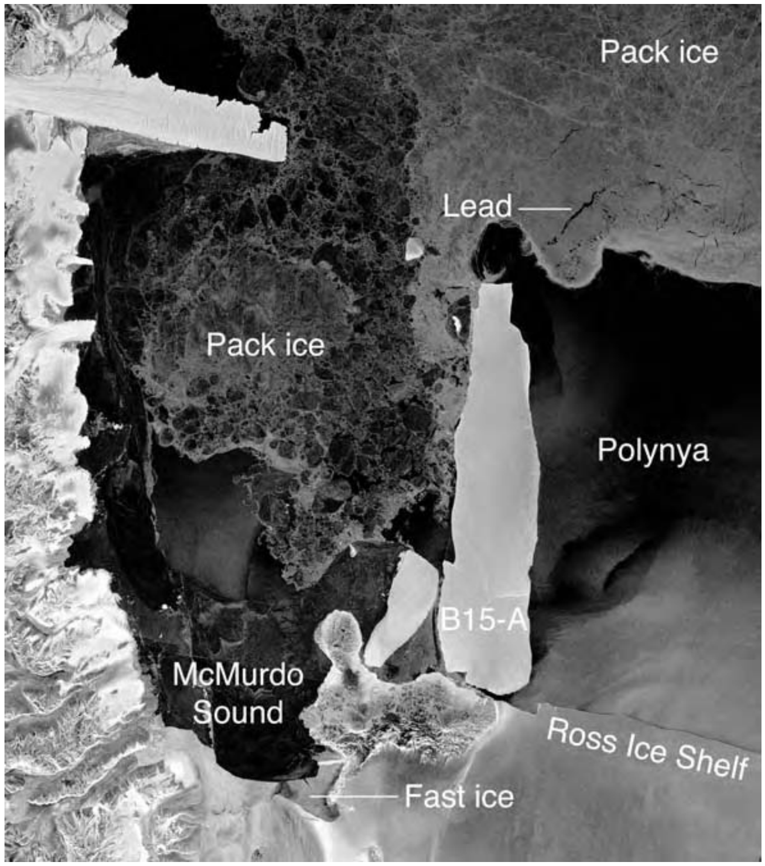
SEA ICE: TYPES AND FORMATION

Introduction

Sea ice is not simply frozen seawater. It is a complex and heterogeneous material of many different types and characteristics that reflect the conditions and processes of formation, and the subsequent history of the ice. "Ice types" includes the ages and stages



RADARSAT-1 synthetic aperture radar image of a 295 km by 330 km region of the southwestern Ross Sea on December 27, 2002. The image shows fast ice in McMurdo Sound, various ages and stages of ice development in the pack ice, iceberg B15-A abutting Ross Island, and the polynya that opens at this time each year to the north of the Ross Ice Shelf. (Copyright Canadian Space Agency.)

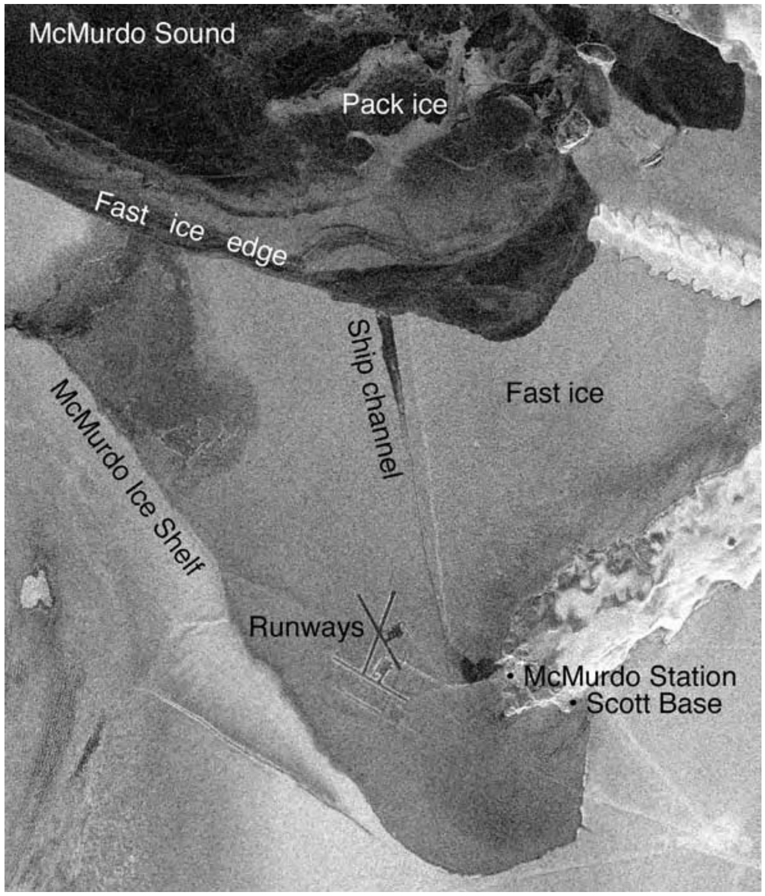
of sea ice development at scales of millimetres to kilometres, as well ice features and characteristics at larger scales of tens to hundreds of kilometres. “Ice formation” describes the actual freezing of seawater and the thickening of the ice cover by different ice growth processes.

Twenty-first-century scientists continue to describe and classify sea ice types and formation using terms that were coined primarily by explorers and whalers in the nineteenth and twentieth centuries. For them, even summer sea ice was an obstacle to be overcome in underpowered vessels not designed particularly well for navigation in ice. Today, modern icebreakers and icebreaking research vessels take scientists into the Antarctic sea ice cover in all seasons to study ice types and formation, and how they affect: (1) ice crystal texture and microstructure; (2) ice thickness; (3) the electrical, mechanical, optical, and thermal properties of the ice; (4) microbial communities and primary productivity within the ice; and (5) heat and mass exchange between the ocean and atmosphere, and thus weather and climate.

Ages and Stages of Sea Ice Development

The age of sea ice varies between just a few seconds and a few years. The broadest categories of sea ice age are first-year ice and old ice. First-year ice is sea ice of no more than one winter’s growth. Old ice is sea ice that has survived at least one summer’s melt. Old ice includes second-year ice (survived one summer’s melt) and multiyear ice (survived two or more summers’ melt). In practice, whether the ice is viewed from a ship, from the air or from space, or investigated directly by, for example, examination of ice core samples or by ice thickness measurements, it is not easy to distinguish between second-year ice and multiyear ice. Consequently, the term old ice is not often used and scientists prefer, instead, the term multiyear ice to describe any ice that has survived one or more summers.

It is not always easy to unambiguously distinguish between first-year and multiyear ice, either. But, viewed from a ship, multiyear ice is likely to have a



RADARSAT-1 synthetic aperture radar image of a 26 km by 32 km region of southeasternmost McMurdo Sound on November 21, 2002. The image shows new ice in the coastal zone of the pack ice beyond the fast ice edge, runways on the fast ice, and the refrozen ship channel cut in the ice by US Coast Guard icebreakers in January 2002. (Copyright Canadian Space Agency.)

higher freeboard because it is thicker than first-year ice, and to have a deeper snow cover because snow has accumulated for longer than on first-year sea ice. Ice thickness measurements and examination of the snow cover and ice core samples might confirm that a piece of multiyear ice has been correctly identified. It is rare for the snow on Antarctic sea ice to melt completely away each summer, but it does metamorphose such that it can be distinguished from snow on first-year ice on the basis of differences in density, grain size and morphology, and stratigraphy. Examination of ice cores reveals variations in ice crystal texture and stratigraphy that can be used to interpret the history and thus age of a piece of ice.

First-year ice is further subdivided into the following categories: new ice, young ice, thin first-year ice, medium first-year ice, and thick first-year ice. New ice includes frazil ice, grease ice, slush, shuga, nilas, and pancake ice. Young ice includes grey ice and grey-white ice. Each of the new ice and young ice types are easily distinguished by eye from one another, since they have distinctive sizes, shapes, surface topography and greyness. As the names suggest, thin, medium and thick first-year ice are classified according to their thickness (i.e., 0.3–0.7 m, 0.7–1.2 m, and >1.2 m, respectively). Most Antarctic first-year sea ice falls into the thin and medium categories, and they are easily distinguished from new and young ice.

The first ice to crystallize on the sea surface is composed initially of spheres, which quickly become discs with diameters of no more than 2–3 mm, and then starlike crystals. In calm conditions (little or no wind, no waves or swell), the stellar crystals grow rapidly across the water surface to form a continuous skim of thin, level ice known as nilas, a Russian term. A snow-free nilas surface has a very dark appearance because it is thin and thus has a high optical depth (i.e., it is transparent and light can pass through it to the underlying water). The thickness of nilas increases by a process known as congelation, in which further ice forms as water freezes onto the bottom of the ice skim or sheet. As nilas thickens and less light passes through to the ocean below, the appearance of the ice changes from dark (<0.05 m thick) to light (0.05–0.1 m thick).

Once nilas reaches a thickness of 0.1 m, it enters the young ice category. Snow-free young ice appears grey (0.1–0.2 m thick) and grey-white (0.2–0.3 m thick). These terms describe its changing appearance as it grows thicker, by congelation, and becomes more optically opaque (i.e., it is no longer transparent and its appearance brightens as light scattering and reflection increase).

Conditions are often not calm in Antarctic waters and the spherical, discoid, and stellar ice crystals collide and break down into small fragments known as frazil ice. The suspension of frazil ice crystals is often herded by the wind to form a soupy layer known as grease ice, that gives the water surface a greasy or matte appearance. Slush is similar in appearance to grease ice, but forms as snow is deposited on the water surface. Shuga is Russian for marble-sized, spongy, white lumps that form among grease ice and slush. Where there are no waves or swell, grease ice and slush can freeze and form nilas.

In turbulent seas the action of waves and swell will rapidly transform frazil ice, grease ice, and slush, and occasionally nilas, into pancake ice. Pancakes are roughly circular, with diameters varying from a few centimetres to as much as 5 m. Most pancakes form from frazil ice and grease ice and have raised rims due to jostling and collisions, which pump frazil-loaded water onto the edges of the cakes. This also progressively enlarges the pancakes, which gradually harden and solidify as the frazil ice crystals freeze together.

The significance of pancake ice in the Antarctic context became apparent in 1986 during the first Winter Weddell Sea Project aboard the FS *Polarstern* (Germany). The sea ice scientists realized that ice formation in a "pancake-frazil cycle" was the source of most of the first-year ice observed between the open ocean and the coast, a distance of 1500 km (Wadhams, Lange, and Ackley 1987; Lange et al. 1990). As the ship penetrated into the ice cover from the northern ice edge, the following sequence was observed: (1) the pancakes began to raft, or ride up on each other, due to the continued influence of waves and swell, and freeze together into thicker and larger pieces of ice known as cakes; (2) as the influence of the waves and swell dwindled, the cakes coalesced into larger pieces of ice known as floes; and (3) ultimately, the floes coalesced into a continuous sheet of first-year ice, in which it was still possible to see the roughly circular outlines of the original pancakes and cakes through the thin snow cover.

An ice cake is any relatively flat piece of sea ice less than 20 m across. Floes are any relatively flat piece of sea ice more than 20 m across. Floes can reach enormous sizes and they are subdivided according to their horizontal extent: small (20–100 m), medium (100–500 m), big (500–2000 m), vast (2–10 km) and giant (>10 km). Sea ice is rarely flat. The pancake-frazil cycle creates a rough ice surface of rafted pancakes and cakes with their characteristic raised rims. Nilas and young ice remain flat only as long as they are not subject to deformation that mechanically thickens and roughens the ice by rafting and ridging.

The Antarctic Sea Ice Cover

The stages of sea ice development from millimetre-sized frazil ice crystals to kilometre-sized ice floes occur at small to medium spatial scales. At the largest or ocean scale, over distances of tens to hundreds of kilometres, the Antarctic sea ice cover can be divided into two zones: pack ice and fast ice.

Fast ice, sometimes also referred to as landfast ice, forms and remains along the coast, where it is attached to the land, to an ice wall, to an ice front, or between glacier/ice tongues, grounded icebergs, and shoals. Fast ice forms in place by the freezing of seawater and by the adfreezing of pack ice floes to the shore or to the seaward edge of the fast ice. Extending as much as a few tens of kilometres offshore, it moves vertically in response to tides and waves, but is otherwise stationary. Each November the fast ice attains a maximum area of approximately 550,000 km^2 (Fedotov, Cherepanov, and Tyshko 1998) or about 3% of the maximum area of pack ice around Antarctica.

The pack ice is the much larger expanse of sea ice that occurs seaward of the fast ice. It is a highly mobile ice cover, where the floes move in response to tides and waves, and, most importantly, to the wind and ocean currents. The latter cause the ice to move, or drift (pack ice is sometimes referred to as drift ice), over the ocean surface at rates of many kilometres per day.

There is a large seasonal variability in pack ice extent, which is nowadays measured routinely on a daily basis using satellite remote sensing from space. At the end of summer (i.e., late February/early March), the pack ice reaches a minimum extent of approximately 4,000,000 km^2. At the end of winter (i.e., late August/early September), it reaches a maximum extent of approximately 19,000,000 km^2. Evidence from whaling and ice core records suggest that there was a significant decrease in Antarctic maximum ice extent during the twentieth century, but this is subject to some debate (de la Mare 1997; Ackley et al. 2003; Curran et al. 2003).

As a consequence of the large seasonal variation in ice extent, ~80% of the Antarctic pack ice at the end of winter is first-year ice. In contrast, the Arctic pack ice is ~50% first-year ice at the end of winter. Since the discovery of the pancake-frazil cycle in the Weddell Sea in 1986, sea ice studies aboard other research vessels elsewhere in Antarctic waters have revealed the widespread occurrence of frazil ice and grease ice, and their transformation into pancakes, cakes and floes. Consequently, it is widely accepted that the pancake-frazil cycle is vital to the rapid, northward expansion of the Antarctic first-year pack ice each year.

Pack Ice

In addition to *Polarstern,* other icebreaking research vessels entered into service in the late twentieth century. The *Nathaniel B. Palmer* (USA) and *Aurora Australis* (Australia) in particular made it possible to pursue more systematic, quantitative and process-oriented studies of ice types and formation in the pack ice than had previously been accomplished. The discovery of the pancake-frazil cycle is an important example of this.

Prior to the appearance of the modern, icebreaking research vessels that could spend weeks in the pack ice for scientific purposes, the knowledge and understanding of ice types and formation was of a more qualitative nature. For most vessels entering the pack ice, it was an obstacle to be overcome in as short a time as possible en route to the coast to explore the continent and even reach the South Pole, and to supply research stations and bases. Any scientists aboard these vessels could do little more than observe and describe the ice cover.

Coupled with remote sensing from space and computer modelling, the modern research vessel-based studies have allowed a much broader view of the pack ice and the complex processes and interactions that occur there. For example, synthetic aperture radar (SAR) remote sensing at the time of maximum ice extent, from the open ocean to the coast, often a distance >1000 km, has revealed that the pack ice can be subdivided into as many as five zones: (1) a pancake zone at the seaward edge adjacent to the open ocean; (2) an outer first-year ice zone, where the generally loosely packed ice cover is composed of cakes and small to big floes; (3) an inner first-year ice zone, where vast and giant floes are often tightly packed; (4) a multiyear ice zone; and (5) a coastal zone of open water, and new and young ice immediately seaward of the fast ice or shore (Morris, Jeffries, and Li 1998). Zones 1–3 correspond to the zones encountered by FS *Polarstern* in 1986 in the Weddell Sea where the full significance of frazil and pancake ice was realized. Not all regions of the pack ice have multiyear ice zones because the pack ice recedes as far as the coast in summer.

Open water and new and young ice are common immediately adjacent to the coast and fast ice edge because winds blowing off the continent move the pack ice away from the shore, creating a shore lead or a polynya. A lead is an opening, often linear and extending for many kilometres, within the pack ice. Leads open and close, rather like a concertina, as the pack ice drifts with the wind and ocean currents. Once open, a lead can quickly freeze over as nilas and young ice grow. The closing of a lead squeezes the thin ice cover, and mechanically thickens the ice by rafting and ridging.

In many locations the offshore winds are funnelled by the topography inland so that they cross the coast at particularly high speed. These cold, katabatic winds cause locally extensive, recurrent and predictable areas of open water and new and young ice known as polynyas. Ice production is often so great in these coastal polynyas that they are sometimes referred to as ice factories. They are also regions of intense heat and mass transfer from the ocean to the atmosphere, and ocean water modification and transformation.

Because ice floes are in almost constant and often rapid motion due to winds and ocean currents, there are always leads and cracks and other openings somewhere in the pack ice. Leads are particularly important for navigation through the pack ice, and, like polynyas, sites of intense heat and mass transfer from the ocean to the atmosphere, and ocean water modification and transformation.

The occurrence of open water within the pack ice gives rise to the term ice concentration. Expressed in tenths, this is a measure of the amount of ice and open water in the pack ice. For example, a 10/10 ice cover is all ice and no open water, and if it was thick first-year or multiyear ice it would be a challenge for even a modern icebreaker to navigate. On the other hand, a 5/10 ice cover (50% ice, 50% open water) of thick first-year ice or multiyear ice could be negotiated by an ice-strengthened vessel.

The terms *ice area* and *ice extent* can be explained in the context of ice concentration. For example, a 10 km × 10 km region of pack ice with 7/10 concentration has an ice area of 70 km^2 and an ice extent of 100 km^2. Ice area describes only the area of ice. Ice extent describes the total area of ice and open water, and is always greater than ice area. Areas where ice concentration is less than 15%, mostly at the ice edge adjacent to the open ocean, are typically not included in calculations of ice extent.

The pancake zone is part of the Marginal Ice Zone (MIZ), a region where the pack ice is broken up by the flexural stress of waves and swell penetrating from the ocean (Wadhams 2000). The width of the MIZ is defined by the distance from the ice edge to which waves and swell can penetrate and break up the ice cover. For example, a severe swell that was observed concurrently from space by SAR and by scientists aboard *Nathaniel B. Palmer* in late August/early September 1993 in the western Bellingshausen Sea penetrated almost 450 km into the outer first-year pack ice and broke up a consolidated ice cover of small to big floes into a looser ice cover of ice cakes (Morris, Jeffries, and Li 1998). The penetration distance of waves and swell into the pack ice varies from a few tens to hundreds of kilometres; consequently, at times the MIZ will include both the pancake zone and the entire outer first-year pack ice zone.

Fast Ice

Prior to the advent of the icebreaking research vessels, quantitative scientific and engineering studies of ice types and formation focussed on the fast ice because it was easily accessible to researchers at coastal research stations, and because its very presence affected the operation and viability of those stations. McMurdo Station (USA) and Scott Base (New Zealand), located on the shore of McMurdo Sound, illustrate the role of fast ice in Antarctic operations and why it has been the subject of numerous scientific and engineering investigations.

McMurdo Station and Scott Base are conveniently located for scientists and engineers, who can easily drive from the land onto the fast ice, or take a flight by helicopter, to reach their study sites. On the other hand, depending on the time of year McMurdo Station and Scott Base are also separated from the pack ice or open ocean by the fast ice and a distance of many kilometres to the ice edge.

Most people arrive at and depart from McMurdo Station and Scott Base by air, and between early October and mid-December many aircraft operate from a temporary airfield on the fast ice. Fundamental to the safe operation of the airfield, because it affects the load-bearing capacity or strength of the ice, is knowledge of the ice thickness, which is determined by prior conditions and processes of ice formation.

The ability to move people and supplies between New Zealand and McMurdo Sound, and between McMurdo Sound and South Pole and other distant continental locations, aboard aircraft that land on the fast ice has great scientific and operational value. However, the fast ice is also an obstacle to the annual and vital resupply by sea of McMurdo Station and Scott Base. This occurs in January and February, and it is rare that the fast ice breaks up and drifts away so that McMurdo Sound opens naturally before the arrival of the fuel tanker and container ship. When it does occur, the natural breakup of the fast ice is promoted by the thinning of the ice due to bottom melting, and by the retreat of the Ross Sea pack ice to the north, which exposes the thinner and weaker fast ice to penetrating waves and swell that fracture it into small pieces. They then drift away northward into the open Ross Sea, often aided by southerly winds. The fast ice subsequently forms again as the sound freezes over beginning in March/April.

Since the supply ships must reach McMurdo Station and unload before the natural breakup of the fast ice, a US Coast Guard icebreaker cuts a channel through the fast ice and escorts the ships to the ice pier. Under normal circumstances this is a fairly routine operation for a single icebreaker to complete with minimum difficulty. However, circumstances were very different in January 2002, 2003, and 2004, when, because of thick multiyear ice that had persisted in the sound since 1999, two icebreakers were needed to break through to the ice pier.

The extreme ice conditions in McMurdo Sound were due to incomplete natural break out of the fast ice in 1999–2001 compounded by the effects of a number of icebergs, including the massive B-15A iceberg, that grounded on the seafloor at the north side of Ross Island in late 2000. It is believed that the icebergs changed the water circulation in McMurdo Sound, primarily by diverting the inflow of relatively warm seawater and thus reducing melting at the base of the ice in summer, and by sheltering the sound from the ocean waves and swell that contribute to the breakup of the thinning fast ice. Consequently, the ice grew older and thicker, and by January 2004 some of the multiyear ice was as much as 8 m thick. The maximum thickness of first-year fast ice in late winter in McMurdo Sound is typically only 2–3 m.

Most nations do not attempt to break through the fast ice that separates their stations from the supply vessels that have negotiated the pack ice, often with some difficulty. Instead, the ships tie up at the ice edge and transfer their cargo to the fast ice for transshipment to shore across the ice, which is often many years old. In fact, the oldest sea ice in Antarctica occurs in the fast ice zone.

Ice Formation

Frazil ice and pancake ice are not just distinctive ice types that are vital to the early and rapid development of the sea ice cover each autumn. The pancake-frazil cycle is also considered to be an ice formation process. But, once the ice cover has become established in this fashion, frazil ice no longer plays an important role in ice thickening by the freezing of water. This is accomplished primarily by two other widespread ice formation processes: congelation ice and snow ice.

Congelation was mentioned earlier in the context of the thickening of nilas. It grows at the bottom of any ice cover when there is a negative temperature gradient—the temperature at the top is lower than the temperature at the bottom—in the ice and snow, if present, and the resultant upward conductive heat flux exceeds the ocean heat flux at the bottom of the ice. If these conditions are met, the latent heat created by freezing at the bottom of the ice is conducted upwards to the atmosphere. Congelation sea ice has a distinctive columnar texture of vertically oriented crystals.

Snow ice formation occurs at the top of the ice. It is frozen slush that forms either when the snow cover is flooded by seawater washing over the ice, or when the mass of snow accumulated on the ice is sufficient to push the ice surface below the sea surface. In the latter case, seawater either flows up to the top of the ice via fractures or via networks of brine channels in the ice. The importance of snow ice was first realized during the Winter Weddell Sea Project in 1986 (Lange et al. 1990) and it has subsequently been shown to occur throughout the Antarctic pack ice (Worby et al. 1998; Jeffries et al. 2001).

Snow ice has a distinctive granular crystal texture that is quite different from the columnar crystal texture of congelation ice. Frazil ice also has a granular appearance and it is difficult to distinguish it from snow ice on the basis of crystal texture alone. To differentiate between frazil ice and snow ice, and determine their relative contributions to ice formation, it is necessary to measure the stable isotopic composition (typically oxygen-18/oxygen-16 ratios) of the ice (Lange et al. 1990).

The snow on the ice surface plays an important role in both congelation ice and snow ice formation. In the case of congelation ice, the snow affects the freezing rate at the bottom because snow has a much lower thermal conductivity than ice and is therefore an effective insulator. Couple the lower thermal conductivity (a measure of the ability of a material to conduct heat) to an increasing depth of snow and thus less negative temperature gradients, and the effect is to decrease the rate of congelation ice growth. Once the snow depth reaches a critical value and has sufficient mass to sink the ice, congelation ice growth ceases as the ice surface is flooded with seawater and the temperature gradient swings from negative to zero. Congelation ice growth will not resume until the slush has frozen completely and a negative temperature gradient has been restored to the entire ice thickness, thereby allowing heat conduction to resume.

In some areas of the pack ice, primarily in deep water regions beyond the continental shelf, there is so much heat in the ocean itself (the ocean heat flux) that congelation ice growth is not only not possible, but bottom ice growth is reversed (i.e., melting occurs). Thinning the ice by bottom melting increases the likelihood that it will sink under the mass of snow accumulating at the surface, leading to flooding and snow ice formation. Consequently, the amount of snow ice in floes often exceeds the amount of congelation ice, if it is present at all, and sometimes even the amount of frazil ice (Jeffries et al. 2001). Snow ice formation plays a vital role in simply maintaining the thickness of ice floes, let alone increasing their thickness in some deep water regions.

Congelation ice is more common in the pack ice and fast ice of the shallower waters over the continental shelf (Eicken and Lange 1989; Jeffries and Adolphs 1997; Jeffries et al. 1993; Gow et al. 1998). This has been attributed to a combination of lower air temperatures, thinner snow cover and lower ocean heat flux than the more northerly pack ice regions. Antarctic coastal waters also promote the formation of platelet ice, which has been found under and within pack ice floes and fast ice.

Platelet ice was first described in McMurdo Sound by scientists with the ill-fated British Antarctic *(Terra Nova)* expedition of 1910–1913 (Wright and Priestley 1922). It is associated with the outflow of cold, low salinity, and thus low density, water from below ice shelves and glacier/ice tongues. As the low-density water rises through the water column and decompresses, it supercools and platelet ice crystals form. They grow in the water column, where they have been mistaken for swarms of krill in echosounder charts (Dieckmann et al. 1986), and float upwards and accumulate against the bottom of pack ice floes or a fast ice sheet. Or, they grow only when the supercooled water finally comes into direct contact with the bottom of the floes or fast ice. Either way, the platelets initially form loose billows of ice crystals that are subsequently incorporated into the overlying ice as the water surrounding the platelets freezes by congelation (Eicken and Lange 1989; Jeffries et al. 1993; Gow et al. 1998).

The snow cover plays the key role in one final ice formation process, one that occurs in the summer and which involves freshwater not seawater. Unlike the Arctic, where the snow cover melts completely and accumulates in ponds on the ice surface in summer, the snow cover on Antarctic sea ice survives the summer. However, there is partial melting and the meltwater percolates down through the snow and refreezes directly on the ice surface as a layer of superimposed ice. It has also been observed in layers perched on top of the slush on seawater-flooded floes. Freezing of the slush in the autumn creates a layer of snow ice and integrates the perched superimposed ice into the total ice thickness. Superimposed ice formation occurs in the pack ice and on fast ice (Kawamura et al. 1999, 2004; Haas et al. 2001).

Antarctic and Arctic Sea Ice

Pack ice and fast ice, and the same ages and stages of sea ice development, occur in the Antarctic and the Arctic. The differences between the two regions are primarily a matter of proportion. The seasonal expansion and contraction of the Antarctic pack ice is much greater than that in the Arctic. Consequently, there is far more first-year ice than multiyear ice in Antarctica, and the area of Antarctic first-year ice at the time of maximum extent is roughly double that of Arctic first-year ice at the time of its maximum extent. Arctic sea ice is more evenly divided between first-year and multiyear sea ice. The pancake-frazil cycle also occurs in the marginal seas of the Arctic, but they cover a smaller total area than the Antarctic first-year pack ice at the time of maximum extent; consequently, frazil ice and pancake ice formation are more widespread in Antarctica than in the Arctic. Likewise, snow ice is more common in Antarctica because snow accumulation on thicker Arctic sea ice is generally not sufficient to overcome its buoyancy and flood the ice surface and the bottom of the snow cover. Arctic pack ice and fast ice growth is dominated by congelation ice formation that is promoted by a lower ocean heat flux and thinner snow cover that provides less insulation from lower air temperatures. Platelet ice has been reported in Arctic floes, but its growth is probably not associated with the outflow of low density water from below ice shelves, and the quantities are likely lower than in Antarctica. Superimposed ice occurs only briefly on Arctic sea ice, where it lasts only a little longer than the snow cover from which it formed. In Antarctica, superimposed ice survives much longer and becomes an integral part of multiyear pack ice floes and fast ice.

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See also **Aircraft Runways; British Antarctic *(Terra Nova)* Expedition (1910–1913); Glaciers and Ice Streams; Ice Shelves; Marginal Ice Zone; Ocean Research Platforms and Sampling Equipment; Pack Ice and Fast Ice; Polynyas and Leads in the Southern Ocean; Priestley, Raymond; Remote Sensing; Sea Ice: Crystal Texture and Microstructure; Thermohaline and Wind-Driven Circulations in the Southern Ocean**

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SEA ICE, WEATHER, AND CLIMATE

A spectacular feature of the Antarctic environment is the presence of large amounts of sea ice. In autumn and winter the amount of solar radiation falling on the Southern Ocean starts to decrease. As a consequence, the sea surface temperatures fall, and when they drop to near –1.8°C, conditions are conducive to the formation of sea ice. This region is subject to frequent, very intense storms. Under the associated strong wind conditions, large amounts of heat are extracted from the ocean, and frazil ice can form. When the winds abate the frazil ice crystals rise to the sea surface where they coalesce into a thin layer of "grease" ice. This eventually forms pancake ice, and continued freezing and horizontal transport produces expansive regions of pack ice. Because the surface of the ice is, in general, much colder than the sea water at its base there is an upward flux (or transport) of heat through the ice. The energy for this heat is provided by the latent heat released as water is frozen onto the bottom of the ice (Stefan's Law). Hence, as the winter proceeds the ice becomes thicker, and new ice also forms farther to the north. When the Sun returns in the spring, the temperatures rise and the northern limit of the sea ice retreats. By the end of summer most of the Antarctic sea ice has melted. The limited amount of ice that does survive ("multiyear" ice) is found in regions close to the Antarctic continent, and in the Ross, Amundsen, Bellingshausen, and Weddell seas (about 40% of the total in the last).

The sea ice distribution is strongly influenced by *dynamic* (mechanical) and *thermodynamic* (melting and freezing) factors. There is a large temperature difference between the cold Antarctic continent and the relatively warm, ice-free ocean to the north. This thermal contrast induces strong and frequent storms over the sea ice region. These, in turn, exert large stresses on the sea ice and may set it in motion. Hence, sea ice can be carried (at rates of up to 60 km in a day) large distances from its point of formation. In particular, ice that is formed in the frigid regions in the southern part of the Weddell Sea is carried north by the Weddell Gyre, and this dynamic transport is the reason the mean ice extent in the Weddell sector (and to the east) is greater than that in any other sector around the periphery of Antarctica.

In addition to the atmospheric wind stresses on the sea ice, it is subject to forces associated with ocean currents, tides, and waves. They also induce stresses and motion in the ice pack, and the resultant deformation of sea ice causes continual fracturing, rafting, and ridging. As a result, areas of open water (with predominantly linear shapes), called leads, frequently appear. When they do there are massive heat transfers from the exposed parts of the ocean to the (cold) atmosphere above. As a result of the heat loss the surface layer of water in the leads cools rapidly, and can refreeze very quickly. Ultimately a balance is reached between the opening and closing of open water areas and the sea ice in a given region will have a spatial concentration of less than 100%.

Whether sea ice is present or absent influences greatly the high latitude communication between the atmosphere and ocean, and hence the regional weather and climate. When the ocean is ice-free these two media interact directly, and the atmosphere provides kinetic energy to the ocean, which subsequently results in wave activity and currents. At the same time the ocean provides the high latitude atmosphere with moisture (through evaporation) and heat. When sea ice is present these interactions dramatically change, and the ice now acts as a rather inefficient intermediary. The atmospheric winds induce a horizontal force on the ice, but whether the ice will move in response to this will depend on a number of factors, including how compact the ice has become. Hence, the underlying ocean loses its local source of wave generation and, to a considerable extent, the momentum to influence currents. In a similar vein, the vertical transfers of moisture and heat change remarkably in the presence of sea ice (it can be seen to be acting as a blanket, and the decoupling effects become more marked for thicker sea ice). As noted above, in ice-free conditions the transfer of moisture and heat is almost always *from* the ocean *to* the atmosphere. When a cold ice surface is present the magnitude of the moisture exchange is greatly reduced and could be upwards (evaporation) or downwards (fog formation). Similarly, the cold ice will now draw down heat from the atmosphere.

This dramatic change in behaviour of these important fluxes can be understood in terms of the surface energy balance over the ice. This balance equates the energy losses and energy gains (steady state) of the floating ice, and allows one to determine other measurements (e.g., the temperature of the ice). The main components of this budget are the net radiation, the latent and sensible heat fluxes from the surface, and the conductive heat flux through the ice. The radiative forcing is conveniently broken up into shortwave (or solar) and longwave (or infrared or thermal) components. Only a small proportion of the solar radiation, which is incident on the ice surface, is involved in this budget because much of the insolation is immediately reflected by the bright surface. The proportion of radiation that is reflected is referred to as the albedo, and over Antarctic sea ice it has typical values of about 0.8–0.9. The sea ice albedo changes during the year and is high when the sea ice is thick, particularly when covered by fresh snow, and lower during the melting season when the snow properties change. The net longwave gain or loss itself depends on the temperature of the surface and the atmosphere. Atmospheric water vapor is a strong absorber of longwave radiation ("greenhouse" gas), and hence part of the infrared radiation emitted by the surface (loss) will be absorbed and re-emitted by clouds and moisture in the atmosphere. This results in a downward flux of longwave radiation *toward* the surface, and the magnitude of this will clearly depend on the amount of the cloud cover (and its height), as well as the moisture content of the air (and hence its temperature). Consequently, the energy balance over sea ice is very different to that over open water, and the net energy balance over a pack ice region of fractional ice coverage is complex.

To understand the associations of sea ice with weather and climate it is important to obtain comprehensive and reliable information on its characteristics. Making relevant observations of sea ice conditions has been very difficult in the past. The oceans over the high southern latitudes are remote and hostile environments, and historically were visited very infrequently. Hence, the number of observations were very few, and most of any such observations were effectively restricted to the region of the ice edge. For practical purposes the only reliable and continuous sea ice observations are those derived from satellites.

By the early 1970s satellites could produce images of the sea ice zone. Since then a range of instruments, including Landsat, Advanced Very High Resolution Radiometer (AVHRR), Synthetic Aperture Radar (SAR), Operational Line Scan (OLS), and the Moderate Resolution Imaging Spectroradiometer (MODIS) have provided very valuable data of the region at high to very high spatial resolution. Visible and infrared satellite imagery is of great value, but these approaches do have their drawbacks—mainly that they require light and cloud-free conditions, two conditions that are not satisfied a significant proportion of the time in the Antarctic sea ice region.

Passive microwave sensors on polar-orbiting satellites can circumvent some of these drawbacks. At many microwave wavelengths the sea ice has a substantially different emissivity to that of liquid water. The sharp contrast between ice and open water in the passive microwave data allows the sea ice distribution to be readily identified (although the summer melt season does pose some problems when the surface of the ice may become saturated). Passive microwave sensors have the advantage for regular and year-round monitoring that their transmission is relatively unaffected by the presence of atmospheric moisture or clouds between the surface and the satellite, and that they do not need the surface to be illuminated by the Sun. There are limitations, however, associated with the use of passive microwave satellite imagery (e.g., the spatial resolution of the products derived from these instruments is relatively modest [about 25 km] and hence cannot identify individual ice floes [nor determine their shapes, sizes, etc.]). However, for the purpose of identifying the interactions of sea ice with weather and climate, that spatial resolution is sufficient for most purposes.

Much of what we know today about the large-scale distribution of Antarctic sea ice has been obtained from the Scanning Multichannel Microwave Radiometer (SMMR) (aboard NIMBUS-7), Special Sensor Microwave Imager (SSMI) instruments aboard satellites of the US Defense Meteorological Satellite Program, and the Advanced Scanning Microwave Radiometer instruments aboard NASA EOS satellites. These instruments have provided snapshots of Antarctic sea ice every second day (and now every day) since 1978. The net effect of all the physical processes discussed previously is to produce a very large seasonal cycle in the area of the Southern Ocean covered by ice, and this is now quantified by nearly three decades of the microwave satellite data. The data reveal that the average maximum coverage is about 19 million km^2 and occurs in late winter/early spring (this area equals about 6% of the total area of the world's oceans), while the minimum coverage occurs in February/March and is about 4 million km^2. Hence most of the Antarctic sea ice is first-year ice. The microwave data provide a comprehensive picture of the horizontal distribution of sea ice concentration. The sea concentration in the pack ice zone in general decreases with distance from Antarctica, which leads to the question of how to identify the location of the ice edge. A practical and well-accepted definition of the ice edge is the point at which the ice concentration drops to 15%.

It was mentioned that not only is the ice concentration important in diagnosing the weather and ice associations, but so too is the thickness of the ice. The Antarctic pack ice assumes different thicknesses (and albedos) as a response to all the influences discussed earlier. Local measurements of ice thickness, obtained from, for example, holes drilled in the ice and from ship-based estimates (as ice breakers turn the ice on its side) are valuable, but for reasons similar to those cited earlier they present only a limited picture of this important variable (and there is obviously a bias for resupply vessels to choose tracks that are expected to have thinner ice). The modest thickness and liquid brine content of Antarctic sea ice makes its measurement a challenge for geophysical (and remote) measurement techniques. Techniques that have been used with some success include airborne and portable electromagnetic (EM) instrumentation, upward-looking sonars tethered to the ocean floor, and ice thickness derived from satellite altimeter measurements of ice freeboard. These techniques have shown that the mean thickness of Antarctic sea ice ranges from 0.5 m to 1.0 m, with thinner ice toward the ice edge and thicker ice in the more southerly regions.

The important role played by leads in terms of modifying the energy balance over the Antarctic sea ice region was discussed above. Important effects are also associated with polynyas. These are regions of open water surrounded by ice but, unlike leads, they do not have a predominantly linear structure. In addition, they are usually much larger, very regionally persistent, and are formed by different mechanisms. One class of polynya is kept open by events such as strong katabatic air flow off the continent whose winds can maintain regions of open water up to a few kilometers from the coast. New ice is continually being formed in this type of polynya, and they are referred to as latent heat polynyas because the surface water is warmed (and kept ice-free) by the latent heat released during the formation of ice crystals. These Antarctic "ice factories" are now believed to play an important role in the maintenance of the global thermohaline circulation. In other regions (away from the coast) so-called sensible heat polynyas can form from heat transferred from deeper waters. For similar reasons to those mentioned, the presence of these polynyas greatly influences weather and climate in the region. For example, it is estimated that the Weddell Sea polynya (which formed during the winters of 1974–1976 and had an area of approximately 350,000 km^2) caused local surface air temperatures to be some 20°C higher than normal, while total cloud cover was about 50% higher than average. It has also been estimated that the mean sensible and latent heat fluxes during the winter months were enhanced by 150 and 50 W m^{-2}, respectively, and precipitation increased by 1 mm day^{-1}.

The insights into the large-scale distribution of Antarctic sea ice provided by the modern satellite products have allowed climatologists and glaciologists to obtain quantifications of the complex connections between sea ice, weather, and climate. The mechanisms by which synoptic weather systems strongly influence Antarctic sea ice formation, evolution, and concentration have been mentioned. By the same token, the sea ice itself influences the synoptic systems. The sea ice distribution is an important factor influencing the distribution of horizontal thermal contrasts (or "baroclinicity") and hence can affect the growth, decay, and direction of motion of cyclonic weather systems. The distribution of sea ice is a critical influence on the magnitude of heat and moisture fluxes to the atmosphere and these, in turn, have major influences on the strength and longevity of these low pressure systems. While the low pressure systems may be regionally confined they do have significant frontal structures that can extend as far as the subtropics, and hence are able to influence weather over much of the Southern Hemisphere.

Sea ice also interacts with climate and on a range of time scales. Ice is of particular importance to the understanding of climate variability because of the role it plays in various feedback processes. One of these is the ice-albedo feedback. Suppose for some reason (e.g., an intense storm or a particularly cool season) the amount of ice in a given region were to increase. The surface albedo (of the ice) will now be much greater than that of the ocean water that previously occupied that region. Hence more solar radiation will be reflected from the region, and this will lead to lower temperatures and encourage further growth of sea ice. Hence this is a positive feedback loop that results in an ultimate ice change greater than the original perturbation.

On a near-global scale, complex relationships have been identified between El Niño occurrences and Antarctic ice variability. The El Niño Southern Oscillation phenomenon is one of the major causes of multi-year and decadal climate (particularly precipitation and temperature) variability over much of the world. During El Niño events a quasi-stationary "teleconnection" pressure wave pattern can be found to originate in the central tropical Pacific Ocean and propagate to high southern latitudes, with nodes in the Amundsen and Bellingshausen seas and in the Weddell Sea. The persistent pressure pattern features associated with these greatly influence the sea ice distribution for the reasons discussed previously. On the other hand, there is evidence to indicate that Antarctic sea ice conditions in turn can influence the initiation and evolution of El Niño events.

Another major mode of variability in the Southern Hemisphere climate is the Southern Annular Mode. This mode essentially represents a predominantly meridional (i.e., north-south) exchange of mass between 40° and 65° S. In the "positive" phase of the mode meridional pressure gradients over the mid- to high latitudes are increased and stronger westerlies are experienced over that domain (and weaker westerlies in the "negative" phase). Interannual variations in high latitude cyclone behavior are known to be associated with this mode. These hemispheric-scale variations impact on sea ice in accord with the physical processes discussed previously. The disposition of the Antarctic sea ice is also believed to affect this mode.

As a final example of the range of sea ice–climate associations, the role of sea ice in driving the global thermohaline circulation and the production of Antarctic Bottom Water (AABW) should be mentioned. When the surface waters freeze, most of the salt is expelled from the ice formed. This in turn increases the density of the waters just beneath the new ice and causes a pulse of cold, saline water to flow onto and then off the continental shelf and ultimately descend into the deep ocean. This bottom water can be found over much of the world's oceans and its presence is one reason why the ocean bottom temperatures are close to 0°C over most of the world. The total production of such water masses will depend on the seasonal *range* of sea ice. Because the Antarctic sea ice region has no effective boundary at its northern margin (a situation very different from the Arctic), the sea annual ice range is large (about 15 million km^2). Oceanic climate (and particularly subsurface oceanic structure) is particularly affected by this production of AABW.

Overall these weather and climate links have been explored with statistical techniques applied to the quality sea ice data sets, which the passive microwave satellite sounders have provided for almost three decades. The complex associations are also investigated with a range of numerical computer models which represent our best representations of the physics of weather, climate and sea ice. The coupling of such models has even allowed us to obtain estimates of Antarctic sea ice distributions over time (e.g., the last few centuries).

Ian Simmonds

See also **Antarctic Bottom Water; Atmospheric Boundary Layer; Circumpolar Current, Antarctic; Climate; Climate Change; Climate Modelling; Climate Oscillations; Ice–Atmosphere Interaction and Near-Surface Processes; Pack Ice and Fast Ice; Polar Lows and Mesoscale Weather Systems; Sea Ice: Types and Formation; Southern Ocean; Southern Ocean Circulation: Modeling; Southern Ocean: Climate Change and Variability; Teleconnections; Temperature; Tides and Waves; Weather Forecasting; Wind**

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SEABIRD CONSERVATION

Introduction

The Antarctic region is known for its seabirds: huge colonies of penguins ashore and resting on ice floes and bergs at sea, and an ocean seemingly filled with majestic albatrosses and a myriad of smaller birds wheeling in the wakes of ships, sometimes passing by in flocks so big they might reach to the horizon. In a region of the world that has hardly been inhabited by humans, where natural, seemingly unaltered environments, both at sea and on land, prevail, it might be assumed that all must be well with such a plethora of life. After all, most southern islands are proclaimed national nature reserves, with a very high level of conservation management (and several are World Heritage Sites). The Antarctic continent is well protected via the Antarctic Treaty and its various instruments. Unfortunately, the assumption that all should be well is wrong, and the seabirds of the high latitudes of the Southern Hemisphere face a number of human-induced threats, so severe in some instances that many species are currently deemed to be threatened with extinction.

The region covered in this entry includes the Antarctic continent and the maritime Antarctic, sub-Antarctic, and uninhabited cool temperate islands of the Southern Ocean, as well as the Southern Ocean itself. The threats facing Antarctic seabirds may be conveniently divided into those operating on land (such as disturbance from ecotourism) and those taking place at sea (such as fishery-induced mortality). However, some more general threats, such as from climate change due to anthropogenic causes, may operate in both environments, and their effects may only act indirectly, and thus are harder to observe (for example, from changes in the distribution, abundance, and availability of the prey of seabirds).

The breeding seabirds of the region are classified into four orders. The most iconic are the penguins (Family Sphenisciformes), with five species breeding on the continent, and others breeding on islands in the Southern Ocean, with some overlap. The next order, the Procellariiformes (albatrosses and petrels, collectively called "tubenoses") has the greatest number of species occurring, mainly occurring on the islands, but with a few continental breeding species. The remaining orders of seabirds are the Pelecaniformes (represented by a number of cormorant species) and the Charadriiformes, consisting of gulls, terns, skuas, and sheathbills (the last group, however, not being considered to be seabirds, but rather shorebirds). A number of species of land birds occur on Southern Ocean islands, but these are not considered further.

The most important conservation threats facing Antarctic seabirds are described next, with the species or species groups, and regions, particularly affected identified. For each identified threat, information is given on what has and is being been done to address it, and what actions might still be appropriate to adopt or consider to further the conservation of southern seabirds.

Habitat Alteration

Alteration or outright loss of breeding habitat has affected Southern Ocean islands to a greater or lesser extent. One driving force in the past has been fire, restricted to the drier cool-temperate islands. French Île Amsterdam and Inaccessible Island in the Tristan da Cunha Group have both suffered from comprehensive burning in the nineteenth century, leading to loss of tussock grass and woody vegetation and thus breeding habitat for burrowing petrels. Although such islands remain permanently at risk from fires, current management procedures are such that the risk is low. The introduction of alien plants also may lead to breeding sites becoming less suitable. Feral herbivores have also altered habitats. Examples are the now removed domestic rabbits *Oryctolagus cuniculus* and cattle *Bos taurus* of Enderby Island in the Auckland Islands, and the cattle still present on Île Amsterdam. On the latter island two fences have been built to exclude cattle from the breeding habitats of the endemic and Critically Endangered (facing an extreme risk of extinction) Amsterdam albatross *D. amsterdamensis*. At other islands feral domestic pigs *Sus scrofa* have altered habitats by rooting (and have consumed seabirds directly).

The relatively recent increases in the populations of fur seals *Arctocephalus* spp. at the more southerly islands (e.g., South Georgia and the South Orkney Islands) has led to the alteration of habitats by the trampling of plants, as well as the physical displacement or disturbance of breeding birds, including surface nesters, such as the wandering albatross *Diomedea exulans,* as well as burrowing petrels. Since fur seals are indigenous members of the communities they affect, are recovering from massive exploitation in the nineteenth century, and are specially protected species in terms of the Antarctic Treaty, their expansion presents a conservation dilemma not yet fully addressed. Should nature be allowed to run its course, or should active management, to maximize biodiversity, for example, be practiced?

Habitat alteration on the Antarctic continent appears to be less of an issue, although some seal colonies are increasing in size on the Antarctic Peninsula, displacing breeding penguins, and changes in ice shelves and the positioning of icebergs may cause the displacement and lowered breeding numbers and success of individual colonies of emperor penguins *Aptenodytes forsteri*. At certain localities the establishment of national stations and associated infrastructures has displaced breeding penguins and surface- and crevice-nesting petrels. A notable example is the now-abandoned attempt by the French to construct a "hard rock" airstrip by flattening and connecting a number of small islands in Terre Adélie. At the species level, this is probably not a significant conservation issue. Nevertheless, the establishment of new bases, and any other human activity for that matter, should always avoid displacing breeding seabirds.

Introduced Predators, Avian Diseases, and Human Exploitation

Introduced predators have been, and on some islands continue to be, the greatest risk southern seabirds face on land. Feral domestic cats *Felis catus* are the prime culprit, massively reducing breeding numbers of burrowing petrels, and causing local extinctions of several species on islands such as New Zealand's Marion Island, Australia's Macquarie Island and Australia's Campbell Islands. Thankfully eradication programmes utilizing a suite of methods (shooting, trapping, and use of poisons) at all three islands have been successful, and affected birds are returning to breed in numbers, assisted by the introduction of captive-reared birds in the case of the endemic Campbell teal *Anas nesiotis*. Feral cats still exist on several French sub-Antarctic islands in the southern Indian Ocean, and their eradication, given the proven methods now existing, should become a priority.

Rodents are present on many of the southern islands, where rats *Rattu*s spp. especially have been considered to have reduced the numbers of the smaller burrowing petrels such as storm petrels and diving petrels, including causing local extinctions, although definite evidence is sometimes lacking. Several successful eradication campaigns have now taken place with more planned. The method of choice is the aerial broadcasting of poison bait by helicopter: a technically difficult and very expensive, exercise. Undoubtedly the greatest success to date was the eradication of the Norwegian rat from 11,300 ha Campbell Island in 2001. A similar operation is now planned for even larger (12,785 ha) Macquarie Island, to remove black rats *R. rattus,* as well as rabbits and house mice *Mus musculus*. Until recently, the house mouse was not thought to be direct predators of birds, but on Gough Island in the Tristan Group it has been proven that in winter months food-deprived mice attack and kill the young of the Critically Endangered Tristan albatross *D. dabbenena* and the Vulnerable Atlantic petrel *Pterodroma incerta*. Both species are endemic to the island group. Modelling has shown that neither species is likely to survive such an onslaught, and an eradication feasibility study is to be undertaken in 2006. Once again, this will be a difficult and expensive exercise, and with the largest southern island at which mice have so far been eradicated being only 710 ha in size (Enderby) against the 6400 ha extent of Gough, success cannot be assured. There is now a pressing need to look for mouse predation of seabirds at other islands where both occur, such as on New Zealand's Antipodes Island. Circumstantial evidence of mouse predation on wandering albatrosses on Marion Island has been very recently reported and is being investigated further by South African biologists.

Seabirds breeding on the Antarctic continent and on maritime Antarctic islands thankfully face no introduced predators. The extremely harsh winters, when nearly all birds are absent, would seem to disallow any surviving for very long. In the past when sledge dogs *Canis familiaris* escaped or were allowed to roam free around continental stations, local mortality of penguins occurred. Dogs are no longer allowed within the Antarctic Treaty Area. This has also caused the cessation of another "introduced" predator: the human occupants of Antarctic stations who killed seals to feed their dogs, and in the early days of exploration, to feed themselves. Humans, mainly sealers on the islands, also killed many seabirds for food, and sometimes for their feathers. The most notorious example of such exploitation was the killing and boiling down of moulting royal penguins *Eudyptes schlegeli* (known as "fats") on Macquarie Island for their oil, where the digesters used are now a macabre tourist attraction. Thankfully, the halting of this operation ranks as one of the first conservation successes in the Southern Ocean.

Infectious bacterial and viral diseases can also be considered to be analogous to predators. Much less is known about avian disease-causing agents in the region, but antibodies of the viral Newcastle Disease have been found in southern penguins, and avian cholera, caused by the bacterium *Pasteurella multicida,* has been blamed for causing mortality of macaroni penguins *Eudyptes chrysolophus* on Marion Island and Indian yellow-nosed albatrosses *Thalassarche carteri* on Île Amsterdam, both Vulnerable species with declining global populations. The elimination of an established disease would seem to be much harder an undertaking than eradicating mammalian predators, so the best way of combating the issue is to introduce strict quarantine measures, such as disallowing the importation of poultry products to island stations, and the halting of keeping domestic poultry ashore. The latter has taken place at most, but not yet quite all, sub-Antarctic islands, the former at only a very few to date.

Disturbance and Ecotourism

Undoubtedly human activities in the region have caused deleterious effects on seabirds. These may be temporary, such as caused by the loss of eggs and small chicks of breeding birds frightened off their nests by passing humans (and their vehicles, including aircraft) to skuas *Catharacta* spp. Where disturbance is of a more chronic nature, declines of populations and the abandonment of some breeding colonies can occur. An example is that the numbers of wandering albatrosses breeding within the close vicinity (and within visual distance) of the meteorological station on Marion Island have steadily declined since the station was established in 1967. It is hypothesized that this reduction has been more a case of drastically reduced recruitment by the more sensitive prebreeding birds than due to a lowered breeding success. In effect as breeding birds die, they have not been replaced by new birds, which prefer to recruit elsewhere to less disturbed areas (which may be less suitable habitat). Such an effect is most probably causing the observed shifting of some penguin colonies near Antarctic bases.

Ecotourism in the region is growing apace, and favoured sites to visit are usually "hotspots" for breeding penguins and albatrosses. Most tourist visits are ostensibly well managed, with minimum approach distances and maximum party sizes voluntarily adopted by members of the International Association of Antarctic Tour Operators (IAATO). However, repeated visits within a single breeding season may well lead to a lowered breeding success, as birds are temporarily halted from reaching their nest sites, perhaps leading to chicks missing meals—without overt signs of any disturbance being noted by the visitors, or their guides. Lectures aboard tourist vessels and the issuing of codes of conducts can help educate tourists about such dangers.

Research has shown that apparently oblivious breeding penguins and albatrosses may have accelerated heart rates as humans approach their nests, leading to energy imbalances that could push birds "over the edge" in the harsh environments in which they occur. Minimum approach distances may help address this problem, and research of disturbance effects on wandering albatrosses at Marion Island has suggested that breeding birds should not be approached closer than 25 m. At this island, three more sensitive species (gentoo penguin *Pygoscelis papua,* southern giant petrel *Macronectes giganteus* and Crozet cormorant *Phalacrocorax [atriceps] melanogenis*) may not be approached closer than 100 m when breeding, unless a research permit has been issued. Research itself can also lead to reduced breeding success, but local and national regulations are generally in place to control this (through the use of ethics committees judging project proposals and the issuing of permits by management authorities).

Aircraft pose a special threat to seabirds. Some species seem more susceptible than others to their presence: an incubating or brooding wandering albatross may literally "hang on" to its nest in the face of helicopter downwash, but king penguins *Aptenodytes patagonicus* may start showing signs of nervousness upon hearing a helicopter, before it comes into visual range. Indeed, an overflight by a fixed-wing aircraft at Macquarie Island once caused the death of some thousands of king penguin chicks, which piled up into heaps against rock faces and suffocated as a consequence. This was an isolated occurrence, and although birds continue to be disturbed (southern giant petrels breeding near Antarctic bases, such as on King George Island, South Shetland Islands, are regularly disturbed by aircraft flying overhead), the discussion and adoption of guidelines by the Antarctic Treaty Consultative Parties in 2004 should go some way to solving the problem. Currently aircraft should not fly below 2000 feet (c. 610 m) over colonies and should avoid landing within half a nautical mile (c. 930 m). Similar national regulations exist for most Southern Ocean islands, via Management Plans and Codes of Conduct documents.

Pollution, Ingestion, and Entanglement

Compared to lower latitudes, most especially in the Northern Hemisphere, and along the world's major shipping routes, Antarctic seabirds have largely escaped the effects of pollution. Oil spills in the Southern Ocean tend to be few and far between (and not the result of the loss of huge quantities of crude oil from stricken tankers). An exception was the grounding of the *Bahia Paraiso* in the Antarctic Peninsula region in 1989, when leaked fuel oil caused oiling of local cormorants and other birds.

Pesticides, such as DDT and dieldrin, and PCBs have been found in the bodies of Antarctic and sub-Antarctic penguins, presumably reflecting a global background fallout, but seemingly not at levels that have led to eggshell thinning and reduced breeding success.

Ingestion of surface-floating plastic items, mistaken as prey by a wide suite of southern seabirds from huge albatrosses to tiny storm petrels, is a source of concern, as such nondigestible items may cause physical damage to the gut, release harmful chemicals, and also give a false sense of satiation. Industrial plastic pellets, bottle tops, and broken fragments are all found in seabird stomachs. Plastic items can even be transferred to predatory seabirds such as skuas when they catch and swallow small storm petrels and prions *Pachyptila* spp. whole. Again, the problem is not as bad as it is in, for example, the North Pacific, which is bordered by the industrial world, and no species seem at serious risk from plastic ingestion at the population level.

Seabirds are prone to becoming entangled in fishing equipment and plastics discarded at sea, but whereas such incidents are dramatic when encountered at a breeding colony, it is not thought the levels attained are of particular conservation significance. A more serious concern comes for surface scavenging species, notably albatrosses, giant petrels, and some *Procellaria* petrels, ingesting discarded fish heads with lines and hooks still attached. This can lead to mortality of adults, and even of their chicks if the offending items are transferred during feeding. Fishing regulations aim at reducing the discarding of hooks, so the problem can be solved with sufficient will.

Fisheries and At-Sea Mortality

Most probably the greatest threat facing southern seabirds, outside the more insidious effects of climate change, is the increased levels of mortality that a suite of scavenging species face from longline and trawl fisheries. Long-lining for Patagonian toothfish *Dissostichus eleginoides* around sub-Antarctic islands and over sea mounts has led to massive mortality of albatrosses and the larger petrels as they seize baited hooks, are dragged below the sea surface and drown. Pelagic long-lining for tuna *Thunnus* spp. has also held to much mortality. Other birds die from colliding with the cables of bottom trawls. The high levels of mortality have led directly to most of the affected birds being accorded a high category of threat by the World Conservation Union, and, indeed, of the world's multispecies bird families the albatrosses are now the most threatened with extinction.

The problem is a relatively new one, first coming to attention as a serious threat in the 1980s. It has been exacerbated by the "gold rush" nature of the toothfish fishery with "pirate" (illegal, unreported, and unregulated) fishing vessels plundering the fish stocks without adopting any bycatch mitigation measures. Massive international attention and pressure, still ongoing, from nongovernmental organizations such as the World Conservation Union and BirdLife

International have led intergovernmental bodies, such as the Food and Agriculture Organization of the United Nations (FAO) and the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) to set guidelines and regulations to reduce seabird mortality. Simple mitigation measures such as only setting lines at night and deploying a bird-scaring line above the hook-bearing longline can greatly reduce mortality. The challenge remains to ensure that these and other mitigation measures are adopted by all fishing vessels and that the pirate fishing scourge is driven from the high seas.

Climate Change

The Antarctic continent, the Southern Ocean, and its islands are not escaping the effects of climate change, especially of global warming. Sea and air temperatures are rising at sub-Antarctic islands, ice shelves are breaking up and shrinking around the continent, and the positions of oceanic fronts, and the prey of seabirds that they delimit, are shifting. Direct effects of climate change on seabirds are hard to assess, but, for example, the worldwide decline in populations of rockhopper penguins *Eudyptes chrysocome* may well be ultimately due to climate change affecting the availability of their preferred prey. It seems hard to imagine how such effects can be ameliorated at the regional level, and it can only be hoped that international efforts to curb the emission of greenhouse and other gases will eventually bear fruit, and not too late to allow affected species to recover.

International Conservation Measures

As well as the efforts of the FAO and CCAMLR, several other international initiatives bode well for improving the conservation status of southern seabirds. The Antarctic Treaty Parties are working toward the listing of Specially Protected Species within the Antarctic continent, and the creation and management of Antarctic Specially Protected Areas (ASPAs) lends a level of protection to a number of seabird breeding colonies that might otherwise be overly disturbed by tourists and scientists alike.

A recent and potentially important development has been the coming into force of the international Agreement on the Conservation of Albatrosses and Petrels (ACAP). With most of the sub-Antarctic nations being parties to the agreement, it is expected that collaborative efforts and information exchange will eventually improve the conservation status of the species covered.

A more intractable problem comes from attempting to persuade the various Regional Fisheries Management Bodies (RFMOs) whose areas of jurisdiction overlap with southern seabirds to consider seabird incidental mortality as a problem they must address. However, the role taken by CCAMLR can be seen as an exemplar to followed, and NGOs such as BirdLife International are actively encouraging recalcitrant RFMOs to face up to their responsibilities.

Lastly, moves are afoot internationally to establish Marine Protected Areas (MPAs) on the high seas. If sufficient international will can be garnered, such sanctuaries may go a long way to protecting southern seabirds from various at-sea threats, most especially from fisheries.

JOHN COOPER

See also **Albatross and Petrels, Agreement for the Conservation of; Albatrosses: Overview; Amsterdam Albatross; Amsterdam Island (Île Amsterdam); Antarctic: Definitions and Boundaries; Antarctic Fur Seal; Antarctic Peninsula; Antarctic Treaty System; Auckland Islands; Biodiversity, Terrestrial; Birds: Specially Protected Species; Campbell Islands; Climate Change; Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Cormorants; Crested Penguins; Diseases, Wildlife; Emperor Penguin; Fish: Overview; Fisheries and Management; Gentoo Penguin; Gough Island; King George Island; King Penguin; Macaroni Penguin; Macquarie Island; Penguins: Overview; Petrels: Pterodroma and Procellaria; Protected Areas Within the Antarctic Treaty Area; Skuas: Overview; South Georgia; South Orkney Islands; South Shetland Islands; Southern Giant Petrel; Terns: Overview; Toothfish; Tourism; Wandering Albatross; Wilson's Storm Petrel; Yellow-Nosed Albatross**

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SEABIRD POPULATIONS AND TRENDS

Seabirds are globally recognised as providing a variety of signals (as "bio-indicators") on many aspects of their marine environments. Because seabirds breed and forage within the marine environment year-round and typically for many years, aspects of their biology such as diet, annual breeding success and population size reflect changes in their prey and their physical environment. Perhaps the best studied example is when an El Niño Southern Oscillation (ENSO) occurs in the Pacific Ocean: all breeding seabirds abandon their nests with eggs or chicks, and there is complete breeding failure associated with the altered physical oceanographic conditions (warmer surface waters) and the absence of their prey species.

Seabirds can provide information on marine environmental conditions at time scales ranging from a day to more than a decade and over spatial scales between local to ocean-basins, depending on what questions are being asked, or which data are under examination. Studies have shown that seabirds can provide information on abundance and changes in prey species, levels of marine debris and pollution, the impacts of introduced predators such as cats and rodents, responses to climate-change, and human disturbance at nesting sites.

Many Southern Ocean seabirds are long-lived, with individuals of some species, notably the great albatrosses, known to live for more than 40 years. Individuals of many species of penguins can live between 10 and 20 years, and skuas for more than 20 years. Such long-lived species allow researchers to examine aspects of the Southern Ocean over a spectrum of time scales extending from days to almost half a century. However, these long life expectancies require long-term data to assess and interpret any observed changes and trends in their breeding populations. With the growing awareness of the value of long term data, there are greater efforts being made around the Antarctic and sub-Antarctic islands to collect such data. There are currently data sets for several species of Southern Ocean seabirds that span 50 years (see below for a summary), but most are between 10 and 30 years.

Individuals of the majority of Southern Ocean seabird species breed annually, and research studies report and use annual breeding populations for analyses, comparisons among localities for the same species and assessing long-term trends. Some Southern Ocean species such as Adélie penguins (see following list) are monitored under the CCAMLR Ecosystem Monitoring Programme (CEMP) and additional parameters such as foraging trip durations and arrival mass are measured.

Individuals of some species breed biennially, but their breeding population sizes are generally reported as annual populations. King penguins breed twice in 3 years on average or may breed biennially. Their breeding frequency is dependent on their breeding success during the previous attempt—successful breeders can fledge two chicks in 3 years as their breeding cycle extends for more than 12 months, while unsuccessful breeders will attempt breeding the following summer.

Several methods are used by researchers to assess annual seabird breeding populations. The standard census protocols collect data on the size of breeding populations at the onset of incubation to estimate the breeding effort. Various assessments of population size and trends, comparisons among localities, and the population's conservation status (e.g., IUCN Red List) use these estimates of breeding populations at localities, or for data on the species as a whole. Current estimates of breeding populations reflect the ease with which census data can be collected. For many species breeding on the Antarctic continent, the data may be years or even decades old, collected during the last visit to a colony/locality. Breeding populations close to occupied research stations are more easily and more frequently visited, allowing for long-term data to be collected with relative ease.

Counts are made during field surveys where all nesting birds or all individuals in a colony are counted. Counts can also be derived from aerial or ground photographs. More recently, colony extents are measured from satellite imagery, and a density is used to estimate the breeding population—for example, this approach has been used for the very large king penguins whose breeding population can no longer be estimated by traditional methods.

Above-ground colonial nesters such as penguins are easier to count than burrow-nesting species such as the prions, petrels, diving petrels, and some of the *Procellaria* and *Pterodroma* petrels. Counts of burrow entrances for these species may not accurately reflect the true size of the breeding population, as entrances may be shared among multiple nests and not every burrow may be occupied.

There are very few data on the sizes of the nonbreeding populations (comprising prebreeding, failed, and nonbreeding individuals). In some cases, it is believed the size of the nonbreeding population approaches 40% of the breeding population. Some data for intensively studied species such as Adélie penguins in the Ross Sea may provide data suitable for extrapolation to other localities and to other species. Species that breed biennially, such as some albatrosses, are more difficult to assess abundance and trends as breeding failure in one season can result in these birds joining the breeding individuals in the following season.

The species accounts below are for the species that breed on the Antarctic continent, the Antarctic Peninsula, the South Shetland and the South Orkney Islands. Where additional information is available for these species elsewhere (away from the Antarctic) that is relevant, it has been included here. Nonbreeding species that visit the Antarctic, such as many species of petrel and albatrosses, are reviewed briefly below.

- **Emperor penguin, *Aptenodytes forsteri*.** The total population is currently estimated at 220,000 breeding pairs in more than forty colonies around the Antarctic continent and the Antarctic Peninsula. The species is endemic to the Antarctic. Some colonies have not been visited for more than 30 years. All but two of the known colonies are located on the winter sea ice. Long term (>25 year) data are few—the best-studied colony is that at the French station of Dumont d'Urville in Terre Adélie. This colony has halved in breeding numbers since the initial counts in the 1950s, and changes in the sea ice and nearby Astrolabe Glacier have been identified as contributing to the observed decrease. Tourist vessels have recently discovered a number of small colonies in previously unvisited areas.
- **Adélie penguin, *Pygoscelis adeliae*.** This is probably the best-studied and best-understood of the Antarctic-breeding seabird species. Adélie penguins are the most widely distributed species of penguin in the Antarctic, but not the most abundant (see macaroni penguin, below). The current estimated population of Adélie penguins is approximately 2.3 million breeding pairs. The population is distributed around the Antarctic coastline, with three major population centres in East Antarctica, the Ross Sea, and the Antarctic Peninsula. Several long-term data sets spanning 40 or more years are available from throughout their range and permit trends to be assessed. Breeding populations in East Antarctica have shown sustained and continuing increases since the 1960s, but the reason(s) are presently unknown. The breeding population in the Antarctic Peninsula region has decreased in the last 50 years, largely due to a decrease in the persistence and extent of winter sea ice. The breeding population in the Ross Sea has exhibited a number of trends over the last 50 years, but recent changes have been related to the presence of massive icebergs such as B-15, that have drastically altered the sea ice conditions that have affected breeding success.
- **Chinstrap penguin, *Pygoscelis antarctica*.** This species is confined almost exclusively to the South Atlantic sector of the Southern Ocean, with large breeding populations present on islands of the Scotia Arc and on the Antarctic Peninsula. There are small populations on the Balleny Islands and on Bouvetøya. The current estimate of the breeding population is approximately 4 million pairs. Different populations in the Antarctic Peninsula region have exhibited different trends over the last 40 years, with some populations increasing and others decreasing. The recent increases in the Palmer region have been correlated with regional warming since the 1950s; the same correlates that have been implicated in the regional decrease of Adélie penguins. Increasing populations of Antarctic fur seals have been implicated in population decreases at Bouvetøya.
- **Gentoo penguin, *Pygoscelis papua*.** This species' breeding populations are primarily located on the sub-Antarctic islands, with small populations on the Antarctic Peninsula and islands of the Scotia Arc. The total breeding population is approximately 300,000 pairs. It is difficult to assess annual populations in this species as there are large interannual fluctuations in breeding effort, typically reflecting a combination of deferred breeding and/or variability in recruitment. Further, breeding is less synchronised than other penguin species. Small breeding populations have recently been reported from South America, possibly the result of regional increases. Population trends elsewhere are less consistent.
- **Macaroni penguin, *Eudyptes chrysolophus*.** This is the most abundant species of penguin in the Southern Ocean, with a current estimate of approximately 5 million pairs. Breeding populations are present on the sub-Antarctic islands, the Scotia Arc and the Antarctic Peninsula. Recent surveys in the South Atlantic suggest rapid

decreases approaching 50% in the last 30 years; the cause(s) for this decrease are presently unknown. Populations at some Indian Ocean islands suggest stable or slightly increasing populations since the 1980s. Recent volcanic activity on the McDonald Islands west of Heard Island may have affected the large population there (previously estimated at 1 million pairs).

- **Southern Giant Petrel, *Macronectes giganteus*.** This species breeds at four localities on the Antarctic Continent, on the Antarctic Peninsula, and on many of the sub-Antarctic islands. Recent surveys in the Falkland Islands have increased the estimated global population to approximately 40,000 pairs. Many breeding populations of this species have decreased in the last 40 or more years, primarily due to birds being caught on fisheries' long lines at sea and from human disturbance at nesting localities. Breeding birds at most breeding localities will readily abandon nests with eggs or chicks if disturbed. Southern giant petrels are taken as bycatch in longline fisheries, especially for Patagonian toothfish *Dissostichus patagonicus*.
- **Southern Fulmar, *Fulmarus glacialoides*.** This surface-nesting species is found on ice-free areas of the Antarctic and some sub-Antarctic islands. The breeding population is estimated at 2 million pairs. Only one population has been examined for more than 20 years—that at the French station of Dumont d'Urville in Terre Adélie. That population has shown a small increase since the mid-1960s and exhibits a high interannual variability in breeding numbers due to snow conditions. No other population has been studied, and there are no other data available with which to assess trends. There have been no conservation threats identified for southern fulmars.
- **Antarctic Petrel, *Thalassoica antarctica*.** This surface- and crevice-nesting species is endemic to the Antarctic. There are no colonies under investigation, and the global estimated breeding population is half a million pairs. There have been no conservation threats identified for Antarctic petrels.
- **Cape Petrel, *Daption capense*.** This surface-nesting species is found on ice-free areas of the Antarctic and many of the sub-Antarctic islands. The breeding population is estimated at 75,000 pairs, but this is likely to grossly underestimate the total population. Only one population has been examined—that at the French station of Dumont d'Urville in Terre Adélie, which has been affected by the construction of a hard rock runway at the station. No other threats have been identified for Cape petrels.
- **Snow Petrel, *Pagodroma nivea*.** This surface- and crevice-nesting species is endemic to the Antarctic. Its crevice-nesting habit makes assessing populations and trends difficult. The current estimate of the breeding population is approximately 100,000 pairs. No assessment of population trends is available for this species. Periods of extensive snow fall and sea ice extent appear to affect breeding success, but no other threats have been identified.
- **Antarctic Prion, *Pachyptila desolata*.** This burrow-nesting species is found predominantly on the sub-Antarctic islands and on the Antarctic Peninsula. At present, there are no long term data available for this species from anywhere in its range. It is believed that breeding populations at localities on the Antarctic Peninsula may have decreased. Breeding localities on the Antarctic continent are no longer used. At present, approximately 10% of the estimated global population of 25 million pairs breeds in the Antarctic, but this global estimate has low confidence, and there are no other known population trends. The greatest threat to breeding Antarctic prions comes from introduced predators such as cats and rats that prey on eggs and chicks.
- **Wilson's Storm Petrel, *Oceanites oceanicus*.** Often described as the world's most abundant seabird (a claim for which there is little supporting evidence), Wilson's storm petrels breed on most of the sub-Antarctic islands, the Antarctic Peninsula, and the Antarctic continent. They are crevice-nesting in the Antarctic and burrow-nesting elsewhere. The current global estimate is 3 million breeding pairs, of which half are believed to nest in the Antarctic. This estimate is largely highly conservative as very few surveys of breeding populations have been undertaken, and there are no long term data on trends at any breeding locality. The largest threat to breeding birds comes from introduced predators such as cats and rats that prey on eggs and chicks. Carcasses of adults with plastic particles in their stomachs have been recorded in the Antarctic. The adults had eaten the plastic mistaking the floating particles for food.
- **Black-Bellied Storm Petrel, *Fregetta tropica*.** It is believed that between 10% and 25% of the global population estimated at 100,000 breeding pairs nest at South Georgia, the South Orkney and the South Shetland Islands. Black-bellied storm petrels are burrow-nesting birds, and

most of the breeding population is found on the sub-Antarctic islands. The greatest threat to breeding birds comes from introduced predators such as cats and rats that prey on eggs and chicks.

- **Pale-Faced (Greater) Sheathbill, *Chionis alba*.** This species' distribution is confined to the Antarctic Peninsula, the South Orkney and South Shetland islands, and South Georgia. Few population surveys have been conducted, and the current estimate of 1000 pairs is a highly conservative underestimate. No population trends are available, and no threats have been reported.
- **South Polar Skua, *Catharacta maccormicki,* and Sub-Antarctic (Brown) Skua, *Catharacta lonnbergi*.** Two species of skuas breed in the Antarctic—the South Polar skua, which is found on the Antarctic continent, the Antarctic Peninsula, and the South Shetland Islands, and the brown skua, which is present on all sub-Antarctic islands and on the Antarctic Peninsula. Mixed-species pairs and hybrids have been regularly observed from the Antarctic Peninsula and from Dumont d'Urville. The estimated breeding populations are 12,000 and 11,000 pairs, respectively. The breeding population at Dumont d'Urville has been monitored since the late 1960s and has shown an increase with considerable interannual fluctuations. Populations in the Ross Sea were stable during short periods (less than 20 years), while the breeding population at Palmer increased fivefold since the late 1970s before levelling off in the late 1990s; increases have also been reported in the South Shetland Islands. There are no hypotheses to explain these differing population trends, but changes in rubbish management and disposal at research stations may have affected local populations. No other threats have been identified.
- **Kelp Gull, *Larus dominicanus*.** This species is widely distributed throughout the Southern Hemisphere, with breeding populations present on all southern continents, on the sub-Antarctic islands, and on the Antarctic Peninsula. Many populations have increased, largely due to an increase in food availability from inappropriate human waste management. The global population is estimated at more than 1.2 million breeding pairs, of which the Antarctic population is believed to be fewer than 20,000 pairs. Few surveys have been conducted in the Antarctic Peninsula, so this estimate is preliminary. No threats to the species have been identified.
- **Antarctic Tern, *Sterna vittata*.** This species is somewhat misnamed as there are no breeding populations on the Antarctic continent itself, only on the Antarctic Peninsula and on the sub-Antarctic islands. This species is considered to be the most highly sensitive to human disturbance at breeding sites and will readily abandon nests. Many breeding populations close to research stations and other sources of human disturbance experience almost complete breeding failure and have decreased dramatically in the last 30 or so years. Approximately half of the total population of 60,000 pairs is believed to nest on the Antarctic Peninsula, the South Shetland and South Orkney Islands. Introduced predators such as cats and rats reduce breeding success, and skuas and gulls readily take eggs and chicks from disturbed nests.
- **Blue-Eyed Cormorant, *Phalacrocorax atriceps*.** The taxonomy of the Antarctic species of cormorants is presently under revision, as there may be as many as seven different species. Various authors use various taxonomies for the cormorants breeding on the sub-Antarctic islands and the Antarctic Peninsula. As a result of this confused taxonomy, total breeding population estimates vary considerably, between 15,000 and 40,000 pairs. No threats have been identified for the species or the various island forms.

At least sixteen species of seabirds are known to be regular visitors to the Antarctic, and of these, populations of at least six species (wandering, black-browed, grey-headed and light-mantled albatrosses, northern giant and white-chinned petrels) are believed to be decreasing due to individuals being caught in longline fisheries in the Southern Ocean. Other than global warming, longline fisheries represent the greatest threat to seabirds in the region, with more than twenty species now known to be taken as bycatch on longline fisheries.

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See also **Adélie Penguin; Antarctic Fur Seal; Antarctic Peninsula; Antarctic Petrel; Antarctic Prion; Antarctic Tern; Balleny Islands; Bouvetøya; Cape Petrel; Chinstrap Penguin; Climate Change; Climate Oscillations; Cormorants; Emperor Penguin; Gentoo Penguin; Heard Island and McDonald Islands; Kelp Gull; King Penguin; Macaroni Penguin; Petrels: Pterodroma and Procellaria; Pollution; Seabird Conservation; Seabirds at Sea; Sheathbills; Skuas: Overview; Snow Petrel; South Orkney Islands; South Shetland Islands; Southern Fulmar; Southern Giant Petrel; Wilson's Storm Petrel**

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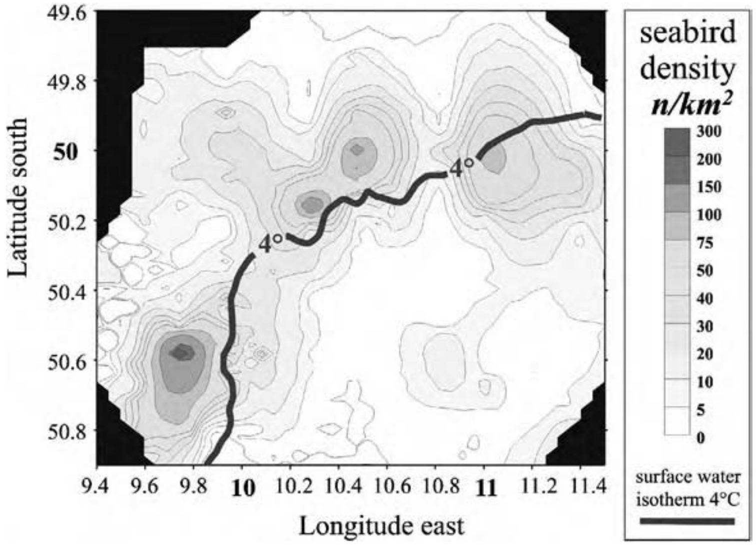
SEABIRDS AT SEA

Fully adapted to a life on the open ocean, seabirds have conflicting interests in coming to land. Solid ground is essential for reproduction or sometimes for moulting. But visits to shore often imply hunger, thirst, discomfort, and all sorts of danger. Out at sea is the place to find food and to fully exploit the capacities of a perfect flying or diving machine. Young seabirds prefer to spend many years out at sea before their hormones urge them to make a first visit to the breeding colonies on shore. But even in adult life, the time spent on shore will be as short as possible.

Much of our current knowledge of seabirds stems from these short periods on shore, mainly during the breeding season. This is especially true for Antarctic seabirds, where poor weather and short periods of light have effectively discouraged biologists to work during the nonbreeding seasons either on land or at sea. Attendance patterns of breeders and the composition or frequency of meals brought to chicks supply some limited information on the at sea life during the reproductive period. But how little do we really know of their fight for survival when they do not return to land? Where do they go, how do they find their way, what do they eat, how do they locate food, what issues are critical for their survival? There are many more questions than answers, and it is only fairly recent that, mainly by technological progress, knowledge of Antarctic seabirds at sea has improved.

The "old-fashioned" way of learning about seabirds at sea is by observations from ships. Over time there has been progress from simply plotting incidental records on maps indicating ranges of occurrence to more dedicated quantitative censuses relating species composition and abundance of birds to environmental factors. The first integrated approach to quantify seabird distribution was developed in the BIOMASS programme *(Biological Investigations of Antarctic Marine Systems and Stocks),* which incorporated standardized bird counts from ships in 300 m wide strip-transects. For some areas, these methods have stimulated the compilation of extensive data-sets. In the Indian Ocean sector, more than 20 years of consistent shipboard observations during resupply trips resulted in distributional maps offering insights in seasonal and migratory shifts, interannual variability, and population trends. In the Ross Sea, marine bird distributions and populations were surveyed in context with habitats and ecology. However, the BIOMASS methods were semiquantitative, with biases originating from birds flying over the transect band during the period of observation. Later international investigations like the *Joint Global Ocean Flux Study* (JGOFS) and the *Global Ocean Ecosystem Dynamics Study* (GLOBEC) made increasing demands on quantitative accuracy of bird abundance. True densities of seabirds in numbers per surface area are needed to model the energy and carbon fluxes between different ecosystem compartments. Two count methods have been developed to account for the error of flux of birds over the transect-strip. These are the snapshot method, which makes intermittent photographic counts of birds in flight, and the continuous vector method, which corrects for relative flight speeds. While these are clear improvements for process studies into the interactions between Antarctic seabirds and their physical and biological environment, integration of different data-sets becomes more complicated.

Records of the distributional abundances of seabirds at sea show the complexity of the strategies that seabirds utilise for their survival. During the breeding season, reproductive tasks evidently limit the spatial range over which seabirds can forage. Breeding penguins may effectively be limited to a radius of some tens of kilometres around the colony, whereas under the same conditions albatrosses and smaller petrels are still able to cover thousands of kilometres on a foraging trip. However, the direction of such flights may not be a free choice but rather determined by wind and weather. The Southern Ocean, which may look dull and uniform to us, is in fact an extremely variable environment with favourable foraging conditions distributed in patches, some of which may be predictable, but others occurring in a seemingly random fashion. Frontal systems and upwellings linked to continental shelf slopes, sea-mounts or ridges are important oceanic features that enhance local productivity through the mixing of water masses. Increased primary production in these areas is passed through the foodweb and ultimately nourishes marine birds and mammals. In the Southern Ocean, the most prominent of such features is the Polar Front. This circumpolar front forms the boundary of northwards flowing cold Antarctic surface water that descends

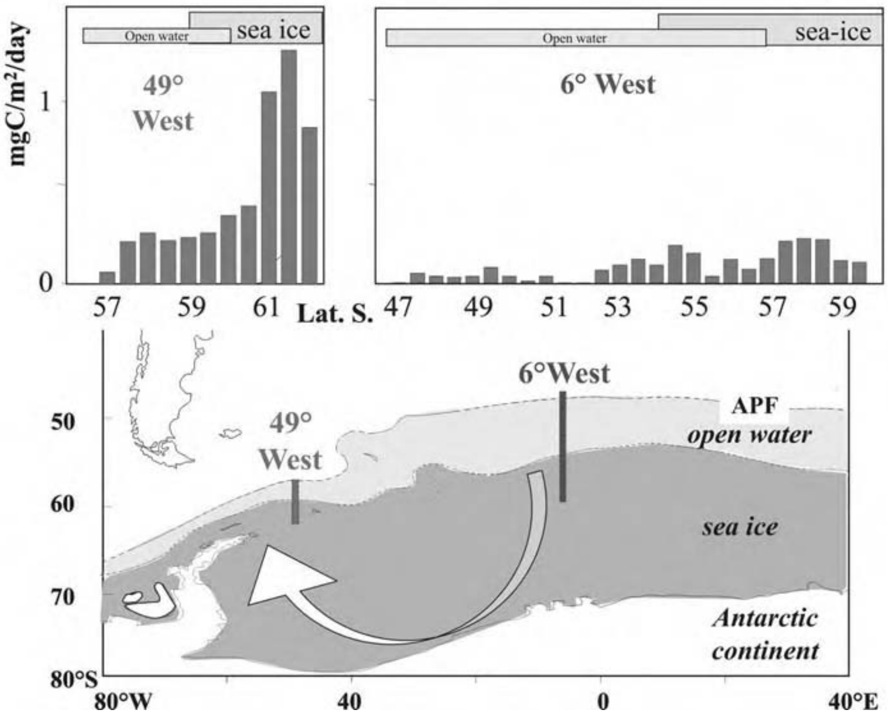


Close linkage between physical features of the meandering Polar Front, characterized by the 4°C surface isotherm and concentrations of birds, mainly Antarctic Prions, January 1–5, 1996.

below temperate waters moving south. Many bird species, especially the tubenoses, but also penguins such as king, macaroni and rockhopper penguins, travel great distances to forage in the Polar Front area. Occasionally the Polar Front is sharply pronounced and detectable by swarms of foraging birds. High density areas of up to hundreds of birds per km^2 were observed in a grid transect over the Polar Front in the first week of January 1996. The birds were associated with patches of high primary production and zooplankton. In turn, these biological phenomena closely followed temperature and salinity discontinuities related to the meandering Polar Front. The main bird species was the Antarctic prion, which probably preyed on small copepods. How seabirds initially locate the Polar Front or other rich foraging areas is not always clear. Part of it may depend on individual or community experience. One definite clue is the use of smell, as a number of seabird species was shown to use the smell of dimethyl-sulfide (DMS) to locate food patches. DMS is released by algae damaged from grazing zooplankton. Once a rich food patch has been located by a number of birds, their foraging behaviour probably attracts others from wider surroundings.

An even more important Antarctic oceanic feature that influences seabirds at sea is the seasonal sea-ice zone. Each winter up to 20 million km^2 of the ocean surrounding the Antarctic freezes up, effectively doubling the size of the frozen continent. At its summer minimum, the residual sea ice still covers an area of around 4 million km^2 teeming with wildlife that prefers the remainders of the ice habitat above the open water. Only a limited number of specialized bird species can efficiently utilize the ice habitat itself, whereas others can only operate along its outer rim. The champion of the ice specialists are emperor penguins, the only seabird that has even escaped from breeding on land. Other birds that associate with the sea ice throughout the year are Adélie penguins, snow and Antarctic petrels. Misguided by the practice of preserving food in freezers, people are inclined to consider ice as a sterile environment and imagine a frozen ocean to be an unproductive desert. Although the water below the sea ice indeed is rather poor, the underside of sea ice itself and infiltration layers are thriving with ice algae and a wealth of microbial life. These are grazed by small zooplankton and krill, which in turn nourish fish stocks and ultimately top predators. Sea-ice foraging appears to be a crucial part of the life cycle of krill: winters with reduced extent of sea ice are followed by lower krill abundance. Although many bird species are not adapted to life in the ice itself, they can still take profit from its productivity when the ice retreats. Materials are released by the melting ice and algal blooms develop along the retreating edge. Many seabirds and marine mammals, including large whales, enter the seasonal sea-ice zone for foraging when the ice retreats.

The importance of sea ice in nourishing Antarctic birds can be illustrated by surveys made in the western and eastern sectors of the Weddell Sea. Food consumption by seabirds was calculated from counts made during repeated north to south transects from open water into the sea ice. The observed pattern of food consumption by the seabird community is very



Seabird food consumption (in units of carbon) in spring and early summer in the open water and ice zones of the opposite sides of the Weddell Sea.

similar on both sides of the Weddell Sea. Bird food intake in sea ice and over the melt zone exceeds that in open water, including that in the productive Polar Front. Food intake by marine mammals follows the same pattern as evidenced by large populations of seals and whale species small enough to maneuver in the pack ice. Overall, the western Weddell Sea is much richer than the eastern part. For the open water zones in the west this may be explained by the high productivity associated with the mixing of a variety of water masses flowing along the Antarctic Peninsula and out of the Weddell Sea. In addition, rich stocks of krill and other zooplankton are concentrated towards the tip of the Antarctic Peninsula by currents flowing out of the Bellingshausen and Amundsen Seas. However, these explanations do not apply to the situation farther south in the pure Weddell Sea water under the ice. The much higher food intake rates for birds in the western ice area may be explained by the fact that the sea ice here has "matured" during the multiyear circular passage with the Weddell Sea Gyre. On the opposite eastern side of the Weddell Sea, the sea ice is always young as it either melts after winter before the ice-associated biology can fully mature, or the floes drift into the Weddell Sea interior. The annual sea ice is thus not a limiting factor for life in the Antarctic but rather a biological engine that supports large populations and diversity of wildlife and structures the life of many seabirds at sea. From this point of view, reductions in the extent of Antarctic sea ice as a consequence of climate change will have a major impact on Antarctic seabird populations.

Observations at sea can only provide limited information on the strategies used by individual seabirds in where they go, which choice of food they take, and how their food is obtained. Fortunately, rapid technological developments are providing a wealth of new information. There has been great profit from the use of ever smaller, smarter, and more energy-efficient satellite-tracking and other positioning devices. One fascinating study after the other on foraging strategies and nonbreeding migrations is being published. Circum-Antarctic navigation by albatrosses, long debated, has now been simply demonstrated. For example, biennially breeding grey-headed albatrosses from Bird Island (South Georgia) were tracked during the 18 months in between subsequent breeding attempts. Tracking data show that a majority of the birds circumnavigates the Antarctic during this period, some of them more than once. The albatrosses travel eastward on the prevailing western winds and have favourite stopping-over areas. Travels between such areas were performed at speeds of up to 950 km per day. A speed record for the full circum-Antarctic travel was established at 46 days. It is only a matter of time before technology is developed that will allow smaller devices that can be fitted to smaller species.

A major result of these seabird tracking data has come from the compilation of all available data from different sources. BirdLife International initiated the integrated analysis of tracking data for all albatrosses and a few petrels. This effort was made because of concern over the population decreases in many albatross species, linked to mortality in longline fisheries. All available information on bird distributions, effort in longline fisheries, and available management regimes was combined in a Geographic Information System (GIS). Such integrated information is indispensable if marine Important Bird Areas (IBAs) or Marine Protected Areas (MPAs) have to be considered by member states of ACAP (Agreement on the Conservation of Albatrosses and Petrels). Protection of breeding colonies or nearby areas is a frequently applied conservation tool but insufficient to protect seabirds during the major part of their life cycles while at sea. Ultimately, the conservation of threathened seabirds will depend on further development of the concept of specially protected or managed areas in the open ocean.

Further improvements in tracking devices will also provide more detail on some of the astonishing aspects of seabird migration. Observations of live birds, beach-cast specimens, and band recoveries have already revealed the general outline of some migration paths. The best known example is perhaps that of the Arctic tern. In between breeding seasons in the far north, Arctic terns commute to the marginal sea-ice zone of the Antarctic. Some Antarctic breeding seabirds perform similar but opposite migrations. Great, sooty, and short-tailed shearwaters are southern hemisphere species that partly forage in the cold waters of Southern Ocean. After breeding, they perform long migrations over the Atlantic or Pacific Oceans flying north to Arctic waters. The crossing of calm tropical waters must present a challenge. Terns use flapping flight and have little problems with the absence of wind and waves. However, the shearwaters, like all tubenosed seabirds, are adapted to flight modes that take advantage of the interactive forces generated by wind and waves, and the calm conditions in tropical waters likely make their travels energetically expensive. At least as spectacular is the migration of the small Wilson's storm petrel, which weighs no more than about 40 g but manages to breed on the hostile Antarctic continental coasts and migrates to the northern hemisphere in winter. Finally, evidence has been growing that at least some of the skuas breeding in the Antarctic, migrate to the northern hemisphere.

Tracking studies can also assist to confirm details of the complicated at sea movements of seabirds when they are bound to frequent visits to breeding sites. For an increasing number of petrel species, a dual foraging strategy is being demonstrated. Irregular nest-attendance patterns of adults, variations in their body mass, and differences in composition of meals brought to chicks indicate that several seabirds use special strategies to ensure their individual survival when raising a chick. It appears that shorter foraging trips to nearby oceanic areas may be sufficient to provide the chick with food but are insufficiently profitable to ensure that the parent can also maintain its own body condition at an adequate level. To solve this problem, several tubenosed species appear to have developed a strategy of alternating short, nearby trips with priority for chick-feeding with long, distant foraging trips during which replenishment of the energy reserves of the adult birds themselves has priority.

The capture of prey at sea by seabirds is a topic where much is still to be discovered. Foraging associations among different species may be important, where predators under water (large predatory fish, diving birds or mammals) may force prey concentrations to the surface and make them available to surface feeding species. Where such foraging strategy is important, this implies that reductions in populations of one of several apparent competitors may not be beneficial to the others but rather disadvantageous because of reduced "catchability" of the prey. As with at sea distributions, technological improvements are providing more and more detail in the field of seabird foraging tactics. Dive depth recorders have shown that emperor penguins may chase prey at depths over 500 m during dives that last up to 20 minutes. But even shearwaters were shown to make dives to 50 m to obtain food. Stomach temperature recorders can indicate frequency of meals and ingested volume in which prey is swallowed, while activity recorders measure to the second any changes in speed and movement of the animal. Videorecording systems, after initial usage on seals, have now been further miniaturised for their application on emperor penguins diving below sea ice. The emperor penguins were found to use a remarkable tactic of diving to several tens of meters depth, but not to catch food there: it appeared that from that depth they were able to locate fishes hiding along the rough undersurface of the ice, which were then captured after a fast upward swim.

In spite of definite progress, much of the life of seabirds at sea remains a mystery. Even a major subject such as quantitative diet information is still very incomplete. There is an increasing body of information on diets delivered to chicks during the breeding season, but very little information is available on food taken during other times of the year. Parent birds may select other prey types to feed chicks than they would for themselves, and an additional problem is that much stomach contents are already fairly digested when adults arrive at the nest. Another problem is that traces of soft-bodied prey may have disappeared completely, or may be underestimated if original prey size is not estimated from remaining parts. In one of the few studies that collected Antarctic seabirds in the marginal ice zone during nonbreeding seasons, fish and squid dominated in the diet of virtually all species and salps were also regularly found. Only a minor part of the food consisted of krill, often considered to be the bulk item in the diet of most common Antarctic seabird species. New indirect methods of dietary research are being developed on the basis of isotope ratios or fatty acids in the tissues of the birds. These methods cannot provide detail of prey species taken, but are particularly useful to indicate general trophic status of bird species of which we have no information at all, or to indicate major differences between breeding and nonbreeding diets.

The life of seabirds at sea still holds many secrets to discover. Step by step, the available knowledge is improving, which is not only the addition of interesting facts but rather a necessary development to enhance conservation and protection of Antarctic seabirds in the environment on which they totally depend, the Southern Ocean.

Jan A. van Franeker

See also **Albatross and Petrels, Agreement for the Conservation of; Albatrosses: Overview; Antarctic Divergence; Antarctic Petrel; Antarctic Prion; Birds: Diving Physiology; Carbon Cycle; Climate Change; Crabeater Seal; Fish: Overview; Food Web, Marine; Marginal Ice Zone; Marine Biology: History and Evolution; Marine Trophic Level Interactions; Pack Ice and Fast Ice; Penguins: Overview; Polar Front; Sea Ice: Microbial Communities and Primary Production; Seabird Conservation; Seabird Populations and Trends; Shearwaters, Short-Tailed and Sooty; Snow Petrel; Squid; Terns: Overview; Weddell Sea, Oceanography of; Whales: Overview; Wilson's Storm Petrel; Zooplankton and Krill**

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SEALING, HISTORY OF

During the eighteenth century, sealers, mainly from the United States and Britain, hunted seals in South America, South Africa, and Australasia. Their quarry was several species of fur seal and the southern elephant seal. As the numbers of sealers increased and populations of seals diminished, they were forced to search farther afield in search of fresh stocks.

Captain James Cook's report that "sea bears [fur seals] were pretty numerous" on South Georgia attracted the attention of many sealers. The first to arrive there was probably an English sealer, Thomas Delano, on *Lord Hawkesbury,* which returned to London with a cargo of fur seal skins in 1787. The first Americans were Elijah Austin, on *Nancy,* and Roswell Woodward, on *Polly,* sailing from New England in 1790 or 1792 (accounts differ).

Edmund Fanning on *Aspasia* took 57,000 skins in 1800–1801, and the estimated season's harvest was 112,000 skins taken by seventeen vessels. In 1822, James Weddell calculated that 1.2 million fur seals had been taken from South Georgia and the species had virtually ceased to exist there. A similar slaughter took place in the South Shetland Islands. Their discovery by William Smith in February 1819 precipitated a rush of sealers to the archipelago. In the summer of 1819–1820, three sealing vessels were at work there, but one year later there were at least forty-four British and American, and two Russian, vessels at work. By the 1821–1822 season there were at least ninety-one vessels sealing around the islands, and the numbers of fur seals were already declining. Not surprisingly, there were hostilities as sealers came into competition.

By only the fourth season of operation, 1822–1823, some vessels were leaving almost empty. HMS *Chanticleer* failed to find a single fur seal in the South Shetlands in 1829, and the species had disappeared from Macquarie Island by 1820, 10 years after the island's discovery. However, populations of fur seals on South Georgia and the South Shetlands recovered sufficiently for sealers to return at intervals throughout the nineteenth century and to take a few thousand or a few hundred in some years.

The drive by sealers to find new stocks resulted in further discoveries in the Antarctic Peninsula region and of several sub-Antarctic islands. The location of sealing grounds were trade secrets for the sealers, who would even leave unreliable members of their gangs ashore while they returned to port, so they could not reveal the whereabouts of seal colonies. However, of the few logbooks that have survived most do not reveal details of vessels' movements. Nevertheless, many sealers contributed to the geographical discovery and exploration of the Antarctic regions. Macquarie and Campbell islands were discovered by Frederick Hasselburg, on *Perseverance,* in 1810 (although he found the remains of a recent shipwreck at Macquarie). The Balleny Islands were sighted by John Balleny in 1839, and Heard Island was also probably first sighted by sealers. In 1821, two sealers, the American Nathaniel Powell and Briton George Powell, combined to search for new sealing grounds to the east of the South Shetlands and discovered the South Orkney Islands.

Some sealing companies were interested in more than commercial gain. The Enderby Brothers, a London shipping, whaling, and sealing company, promoted geographical exploration and the collection of natural history specimens by their captains, but this pursuit contributed to the company's financial problems. John Biscoe, on *Tula,* circumnavigated Antarctica between 1830 and 1833 and discovered Enderby Land, but returned with only thirty seal skins. Peter Kemp, on *Magnet,* working for David Bennett & Sons, discovered Kemp Land on the mainland of Antarctica in 1833 but was drowned on the way home. The best known of the sealer-explorers, however, is James Weddell, who is famous for his deep penetration into the Weddell Sea and observations on wildlife.

Sealers arrived mostly in small vessels; Weddell's *Jane* and *Beaufoy* were 160 and 65 tons, respectively. Others employed larger vessels and took "shallops" of about 30 tons, which were carried in frame and assembled on site. The parent ship remained at a safe anchorage while the shallops visited the seals' breeding beaches along the coast. Sealing gangs also camped ashore while the vessel moved to other beaches. The men lived a hard life in caves, under upturned boats, or in rough shelters built of stones or timber and roofed with timber, whalebone, and canvas. They endeavored to start sealing as early as possible in the breeding season and concentrated on killing cows and young bulls, which had the best skins.

The seals were killed with a 5-foot wooden club and stabbed to bleed; the larger bulls were lanced. Flensing or flaying started as soon as possible, the technique depending on the market to which the skins were taken. Initially, American sealers had a monopoly of the China market, where the skins could be sold at a greater profit. The Chinese shaved the skins and felted the fur for use in winter clothing, although it seems likely they also used the leather. The sealers removed all the blubber, sewed up the flipper holes and then stretched the skin out on the ground to dry. Skins destined for the American and European markets had some of the blubber attached and were piled into a "book" under heavy stones to squeeze out as much water as possible. A day or two later, the book was rebuilt with alternate layers of salt. Care had to be exercised because nicks and cuts in a skin reduced its value, while slipshod salting allowed it to rot. One year, *Pegasus* arrived in London with a prime cargo of skins, but they had rotted and could only be sold as manure.

The European market was mainly for leather, which was used for shoes and gloves. Then, in 1795, a London hatter, Thomas Chapman, discovered a way of removing the long, coarse guard hairs to leave the dense, fine underfur, a very valuable product. The guard hairs have longer roots so, if the skin is carefully pared away from the underside, these are cut and the guard hairs can be combed out, leaving the underfur intact.

From the start, sealers visiting the Antarctic augmented their harvest of fur seal skins with oil rendered from the blubber of elephant seals. Until fur seal skins could be processed into fine pelts, the high quality of seal oil made it the more valuable cargo. A large bull elephant seal yielded about one third of a ton of oil. As with fur seals, killing was indiscriminate, the cows and pups being clubbed and the bulls shot. The blubber was soaked for two days to remove the blood then cut into "horse-pieces" or "blanket-pieces." These were cut into fine slices and boiled in large cauldrons or "try-pots" to render (or try) the oil, which was decanted into a second pot and given a second, and sometimes a third, boiling. The solid residue, the "fritters," was used as fuel for heating the pots, as were the carcasses of penguins. At Yankee Harbour, Greenwich Island, there is a penguin corral above the remains of sealers' huts and a try-pot. Elephant seal oil was used for heating, lubrication, and treating leather, but towards the end of the nineteenth century seal and whale oils were being replaced by mineral oils.

Sealing continued though the nineteenth century, spasmodically toward the end as stocks recovered and were exploited again. Often, and especially at Heard and Kerguelen, whalers took the opportunity to augment their catch of whales by sealing. The last of the old-time sealers and whalers was Benjamin Cleveland, on *Daisy,* who visited South Georgia in 1908 and 1912–1913 and took small numbers of elephant and fur seals.

At this time, a new sealing industry had started on South Georgia. In the 1890s expeditions were dispatched from Europe to investigate the possibilities of whaling and sealing. They met with little success until Carl Anton Larsen established a whaling station at Grytviken, South Georgia, in 1904. Some elephant seals were harvested in the first year, and in 1909 the Falkland Islands and Dependencies government introduced the Seal Fishery (Consolidation) Ordinance to regulate sealing and granted a license to Larsen's company, the Compañia Argentina de Pesca. The operation used obsolete whalecatchers to land sealing gangs at the many bays and coves around the coast of the island during the breeding and molting seasons. The method of killing and dismembering the seals was much the same as in earlier years, but the blubber was taken back to Grytviken to be boiled in the whaling station. Although a logistically minor operation, elephant sealing was economically important because, for a small outlay, it produced up to 2000 tons of high quality oil, which amounted to 16% by volume and 19% by value of Grytviken's total oil production. Sealing effectively ceased with the closure of Grytviken in December 1964 after some 260,950 elephant seals had been killed to produce 83,146 tons of oil. In the early years, ninety Weddell seals, 752 leopard seals, and one fur seal had also been taken. The last sealing at South Georgia was in 1968 from the "pirate" vessel *Run,* later *Sierra,* which took five seals to familiarize the crew with sealing techniques.

Sealing licenses at South Georgia set limits on the harvest. The coastline of South Georgia was divided into four divisions (with some areas as reserves where sealing was forbidden). Only three were worked in any single year and 2000 adult male elephant seals could be killed in each. The quota was later increased to 8000, but a study revealed that the population was declining. As a result, a new regime based on scientific management was instituted in 1952. Under the control of a government-appointed sealing inspector, quotas were set for each division according to its seal population. Only seals above a body length of 11.5 ft (3.5 m) could be taken, and samples were collected to monitor the age composition of the population. As a result, a sustainable harvest developed in which the body size of the seals and therefore oil yield increased.

However, proposals for regulated culling were not new. In 1798, John Leard of the Royal Navy wrote to Lord Hawkesbury, President of the Council for Trade and Foreign Plantations in London, making suggestions for the regulating of the sealing industry with limits on sex, age, and numbers taken. Nothing was done, and Antarctic fur seal stocks were rapidly destroyed, as they had been in other parts of the world. James Weddell had also commented that a sustainable harvest was possible if sealers exercised restraint and did not kill female fur seals at least until their pups were independent.

The experience of elephant sealing shows how a sustainable harvest can be taken where there is strict governmental control. Farther south in the Antarctic Treaty area south of 60° S, no such control existed, and in 1964, the Norwegian vessel *Polarhav* hunted crabeater seals in the pack ice near the South Orkneys. Only 852 were taken, and the expedition was not a commercial success. Although the Antarctic Treaty had banned the killing of native animals, it referred only to land and fast ice. A further international agreement was needed to cover the sea and floating ice, so the Convention on the Conservation of Antarctic Seals was signed in 1972. Fur seal, elephant seal, and Ross seal became fully protected, while catch limits were set for crabeater seal, leopard seal, and Weddell seal. Seals are the subject of local legislation on sub-Antarctic islands outside the Antarctic Treaty area.

Robert Burton

See also **Antarctic Fur Seal; Biscoe, John; Convention on the Conservation of Antarctic Seals (CCAS); Cook, James; Dundee Whaling Expedition (1892–1893); Enderby, Messrs.; Heard Island and McDonald Islands; Kerguelen Islands (Îles Kerguelen); Larsen, Carl Anton; Macquarie Island; Norwegian (Tønsberg) Whaling Expedition (1893–1895); South Orkney Islands; South Shetland Islands; South Shetland Islands, Discovery of; Southern Elephant Seal; Weddell, James; Whaling, History of**

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SEALS: OVERVIEW

Seven species of seals inhabit the Southern Ocean. All belong to Suborder Pinnipedia, which is a term derived from the Latin *pinnipes,* for wing- or fin-footed. Debate is ongoing as to whether this suborder is diphyletic or monophyletic. Of the three families of pinnipeds, only the odobenids (walruses) are not represented amongst Antarctic seals. Worldwide the family Phocidae (true seals) consist of nineteen species in thirteen genera. Antarctic phocids include the four lobodontine pinnipeds: crabeater seal *(Lobodon carcinophaga),* Ross seal *(Ommatophoca rossii),* leopard seal *(Hydrurga leptonyx)* and Weddell seal *(Leptonychotes weddellii)* in addition to the southern elephant seal *(Mirounga leonina)*. Of a total of seven genera and sixteen species, otariids are represented in Antarctic waters by only one genus and two species: the Antarctic fur seal *(Arctocephalus gazella)* and the sub-Antarctic fur seal *(Arctocephalus tropicalis)*.

The Phocidae are characterised by an inability to rotate the hind flippers under the body, which dictates their characteristic locomotion on land or ice (hunching, wriggling, flopping, inch-worming). Also characteristic are the absence of pinnae, a short muzzle, beaded vibrissae, a dark coloured skin, short fur, furred fore flippers and hind flippers, five claws on each fore flipper, generally two teats in females, and internal testes. The hind limbs provide propulsion in water except in leopard seals, which, like the otariids, swim primarily with fore flipper strokes. In the otariids the hind limbs are used in steering when swimming. Otariids can rotate the hind limbs under the body and move on all fours on land. They have pinnae, smooth vibrissae, a light coloured skin, a double layer of fur, partially hairless fore- and hind flippers, four teats in females and scrotal testes. Claws on the fore flippers are vestigial or absent.

With a skull in hand, phocids are easily separated from otariids as they have no supraorbital processes, their nasal bones do not penetrate between the frontals on the midline, and their incisors are not transversally grooved, as in the first two upper incisors of otariids. While males grow larger than females in most species of pinnipeds, the reverse is true for the lobodontine seals. Although sexual dimorphism in size is much less pronounced in phocids than in otariids, the greatest disparity is found in elephant seals, which is the largest species of seal. Adult males reach masses of 2000–4000 kg, while females only reach masses of 400–900 kg. Adults of the lobodontine species weigh 200–600 kg. Adult male fur seals reach masses of 200 kg while the females reach masses of approximately 50 kg. Elephant seals experience an annual catastrophic moult, with the skin sloughing away in large patches rather than the hairs falling out individually, as happens in almost all other species of phocids and all species of otariids.

While Antarctic pinnipeds are marine mammals, and therefore spend the majority of their lives at sea, they are constrained by the need to return to land or stable ice substrates to give birth, to lactate and to moult. However, they feed almost exclusively at sea. As carnivores they typically have differentiated teeth, including incisors, canines, and postcanines. Adapted to both terrestrial and aquatic conditions, all pinnipeds have a similar morphological appearance. They have a coarse pelage of guard hairs, with or without a layer of underfur. Their body shape is adapted to reduce turbulence and resistance (drag) and is thus fusiform. A subcutaneous layer of fat (blubber) provides stored energy, insulation, and buoyancy, and the limbs are relatively short, stout, and modified to form paddle-like flippers. Eyes of seals are relatively large and modified to focus underwater by means of greater corneal curvature and spherical eye lenses, and to see effectively under conditions of reduced light with a well-developed, specialized membrane behind the retina. Physiological processes for diving include slowing of the heart rate (bradycardia), shunting blood from peripheral areas to the brain and heart, a high tolerance for carbon dioxide levels in the blood, a high concentration of haemoglobin in their red blood cells and myoglobin in their muscle tissue, a relatively large blood volume, an ability to withstand enormous pressures at depth, and an ability to avoid developing either nitrogen narcosis (an anaesthetic effect on the nervous system that may lead to unconsciousness and death) or the "bends" (dissolved nitrogen coming out of solution, forming gas bubbles that may cause embolisms and result in death) upon rapid return to the surface.

The four lobodontine species inhabit the pack ice and fast ice zones of Antarctica, and are among the dominant predators in the Southern Ocean ecosystem. Their distribution is circumpolar, and while the ranges of all four species overlap, they also reflect their unique adaptations.

Ross seals are more common in regions of consolidated pack ice, especially during the breeding season, but are also seen in more open pack ice and occasionally on fast ice. They undertake long foraging trips to open water north of the pack ice.

Weddell seals tends to inhabit fast ice or the heavier pack ice close to the Antarctic continent. They use tidal cracks to gain access to shallow benthic waters beneath. They tend to move northward with the expansion of the ice in winter, foraging in open waters. Small groups of Weddell seals, largely isolated from the main populations, may haul out on some of the islands of the Antarctic Peninsula.

Crabeater seals are common in pack ice areas, with the highest densities over the continental shelf. Their distribution also moves northward with the pack ice in winter. While leopard seals are also generally distributed within the pack ice throughout the year they tend to move northward with the expanding pack in winter. Numbers of primarily nonbreeding animals move frequently and regularly to the sub-Antarctic islands (distributed approximately between 40° S and 60° S) during late winter and spring. They are more common at these sites in years in which the pack ice is more extensive. Vagrants occasionally haul out on the southernmost coasts of South Africa, Australia, New Zealand, and South America. Vagrants of the other three species of lobodontine seals are rare and are seldom recorded beyond the sub-Antarctic islands.

The fifth phocid, the southern elephant seal, breeds almost exclusively on the sub-Antarctic islands, but also as far south as the South Shetland Islands in the Antarctic Peninsula. Individuals from all populations of southern elephant seals in the sub-Antarctic also feed within the Antarctic maritime zone, and elephant seals frequently haul out to moult on the Antarctic continent at a number of sites, such as the Vestfold Hills. They share their island haulout sites with one or both of the species of Antarctic otariids. Antarctic fur seals inhabit islands that lie mostly south of the Polar Front, while sub-Antarctic fur seal populations are found on islands to the north of the Polar Front. Populations of both species are present at three islands or island groups north of, but close to, the Polar Front. Breeding colonies of the two species are generally found on beaches of different terrain, which ensures that hybridization is limited at two of the island groups. At the third island, Macquarie Island, the populations are small and breed sympatrically. A small number of adult males of another species of otariid, the New Zealand fur seal *Arctocephalus fosteri,* are also associated with the breeding colonies at Macquarie Island. Hybrids are common within this population.

The breeding season for most pinnipeds is spring or summer, with the Antarctic phocids giving birth between October and December, while the otariids give birth in November and December. Pinniped females give birth to a single offspring after a gestation period of about one year, including a period of delayed implantation of the fertilized egg. Twinning is extremely rare, and twins rarely survive in the wild until weaning. Pinniped males do not care for the young. All otariids have a polygynous mating system and pronounced sexual dimorphism. Mating generally takes place on land. Males defend onshore territories against other males, which results in access by relatively few dominant males to numerous females. These come into oestrus soon after producing their pups and before their first foraging trip to sea. This does not, however, ensure that dominant adult males inseminate all the receptive females within their territory, as alternative male strategies and female choice seem to play important roles. The southern otariid females are income breeders, alternating between periods of foraging at sea and suckling their pups on land. The lactation periods typically vary between four and ten months. Otariid males are capital breeders that gain condition at sea before the breeding season and remain on land without feeding for the duration of the summer breeding season.

The mating systems of the southern ocean phocids vary from polygynous in different degrees (Weddell seals and southern elephant seals) to serially monogamous (crabeater seals), with mating taking place on land and/or at sea. Females of all species are capital breeders, generally storing energy and nutrients in their subcutaneous blubber while foraging before the breeding season. They then come ashore or haul out on ice to fast while nursing their pups for between 3 and 8 weeks. Adult female Weddell seals, however, will forage to some extent during the lactation period.

During the breeding season elephant seals haul out in large aggregations, which may number in the thousands. Females come into oestrus a few days after their pups are weaned. Mating access to females is determined by the dominance hierarchy amongst males. Males generally remain ashore for most of the 3-month breeding season.

During the breeding season Weddell seal females congregate near access holes and tidal cracks in colonies of 10–250 individuals. The mother and pup will remain on the ice for some 7–10 days after parturition. They will then take to the water together on short foraging trips until the pup is weaned. Adult males do not haul out to the pupping sites, but defend underwater territories around access points. This allows them exclusive mating access to a number of adult females. Mating takes place underwater near the end of weaning. Females of the remaining three species of lobodontine seals do not aggregate during the breeding season. Female crabeater seals will be guarded by an adult male, generally from shortly after she has given birth. An adult male and female will form what is known as a mated pair for the 1–2 weeks between weaning and copulation. Subsequent to copulation the adult male may try to find another female with pup and form another mated pair. Adult males do not attend to adult females during the lactation period for either leopard or Ross seals. Auditory displays are used by the sexes to locate one another after the pups are weaned. Mating is thought to take place in the water.

The foraging behaviour and diet of the Antarctic seal is strongly affected by the major seasonal changes of the Southern Ocean, which affects the distribution and abundance of potential prey species, and by the depauperate variety, but great abundance of a number of prey species, especially krill *Euphausia superba*. Krill comprises an estimated 37%–95% of the diet of the crabeater seal. Due to its abundance and biomass, this species of seal is perhaps the most important consumer of this crustacean and is the krill specialist amongst Antarctic seals. Their teeth have multiple cusps that allow them to strain krill from seawater, and their foraging behaviour follows seasonal changes in the behaviour of their prey. During the summer most foraging takes place at night and at depths of less than 50 m. Foraging depths are deepest during dawn and dusk and shallowest during periods of complete dark. In the winter, foraging takes place during the day, and is most likely benthic, taking place at depths of 50–450 m.

Krill also forms an important part of the diet of the leopard seal, and the South Atlantic populations of the Antarctic fur seal. While both species feed on krill year round, it is a far more important part of the diet in winter, with leopard seals feeding on little else. The dentition of leopard seals is also modified for krill consumption, with tricuspid molars. They do, however, also have large canines and molars that allow them to hold and rend warm blooded prey. During the summer they feed on penguins and immature seals (especially of crabeaters), in addition to krill and benthic and pelagic fish. They are also known to occasionally scavenge on whale carcasses.

Antarctic and sub-Antarctic fur seals are also know to eat penguins seasonally, though this behaviour is likely limited to adult and subadult males. In populations away from the South Atlantic, Antarctic fur seals follow a diet very similar to that of sub-Antarctic fur seals, mainly fish and squid. Both species forage at shallow depths but often over deep waters. The duration of foraging trips and their distance from terrestrial haulout sites changes seasonally. During the summer adult females of both species are lactating and therefore forage close (<300 km) to the pupping colonies. During the winter adult female Antarctic fur seals are no longer lactating and forage at distances of up to 1000 km from their terrestrial haulout sites. While adult female sub-Antarctic fur seals continue to feed pups for most of the winter, foraging trip duration is longer at this time of the year. Relatively little is known of the foraging habits of adult males, but it is possible that they forage at greater distances from their terrestrial haulout sites.

Weddell seals also feed on a variety of species of fish and squid, but they concentrate on the abundant Antarctic silverfish *Pleuragramma antarcticum*. They alternate seasonally between benthic and pelagic waters. Foraging dives are typically less than 400 m and up to 15 minutes duration. Both the Ross seal and southern elephant seal are thought to feed mainly on squid, in addition to a number of species of fish.

Ross seals feed at depths of 100–150 m, and their dives seldom last longer than 10 minutes. Elephant seals are believed to eat between 19% and 36% of the entire squid biomass in the Southern Ocean. The fish component of their diet comprises both pelagic and benthopelagic species. While southern elephant seals may dive to depths of 1500 m, for up to 120 minutes, foraging is believed to take place primarily between 300 and 600 m during shorter trips. They may migrate distances of 5000 km to reach foraging grounds, and they show fidelity to these foraging sites. A number of studies have found differences in the diets of adult males and females, with males foraging both pelagically and benthically, while females forage pelagially. Immatures tend to feed more on fish prey species than do adults.

Commercial exploitation of the four lobodontine seals was limited to brief experimental harvests of crabeater seals, which proved commercially unviable. This, and limited harvesting of all four species for food for humans and their dogs, and for scientific specimens, is thought to have had little effect on the size of their populations. Numbers of the lobodontine species are particularly difficult to ascertain, but Crabeater seals are particularly abundant with a population possibly in excess of 15 million. Weddell seals number between 500,000 and 1,000,000, while leopard seals number less than 500,000, and Ross seals number around 130,000.

The southern elephant seals and the two species of fur seals were all driven close to extinction by commercial harvesting within decades of their discovery. The height of the commercial harvest occurred during the nineteenth century. The last commercial harvests of fur seals took place during the 1920s. A limited commercial harvest of southern elephant seals continued at South Georgia up till 1964. Southern elephant seals were primarily taken for their blubber, which was rendered down to high quality oil. Fur seals were killed for their skins. Subsequent to the cessation of harvesting the populations of both species of fur seals and the southern elephant seal began to increase and many islands were recolonised. Today, Antarctic fur seals number more than 4 million and breed at some ten island groups. The largest population is at South Georgia, which accounts for more than 90% of the global total. Sub-Antarctic fur seals presently number over 300,000 at seven island groups. The largest populations are at Gough Island and the Prince Edward Islands. The total for all populations of southern elephant seals is believed to exceed 500,000, approximately half of which come from South Georgia. While many populations of elephant seals have increased in the last few decades, a number are known to be stable or declining slowly. All seven species of Southern Ocean pinnipeds are currently protected by the Convention on the Conservation of Antarctic Seals. Present harvesting is limited to small takes for scientific purposes.

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See also **Antarctic Fur Seal; Convention on the Conservation of Antarctic Seals (CCAS); Crabeater Seal; Diving—Marine Mammals; Fish: Overview; Gough Island; Leopard Seal; Macquarie Island; Polar Front; Prince Edward Islands; Ross Seal; Sealing, History of; South Georgia; South Shetland Islands; Southern Elephant Seal; Squid; Sub-Antarctic Fur Seal; Weddell Seal; Zooplankton and Krill**

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SEASONALITY

The term *seasonality* can be applied to any feature (biological, physical) that varies on seasonal timescales. As a simple illustration, the solar radiation climate (visible light and other wavelengths) anywhere on Earth is defined by latitude and date. At latitudes within either of the polar circles, there are periods with no exposure to sunlight in winter, and 24-hour exposure in summer, the duration of these periods increasing toward the poles.

Antarctic environments include those at the extreme limits (even more so than the Arctic) available on Earth in terms of many seasonally related environmental characteristics—low temperature, presence of liquid water (including precipitation patterns), ice cover, and light. On land, tight seasonal covariance between light, temperature, and water (and interrelated parameters such as freeze-thaw cycles) at latitudes within the polar circles imposes tight limitations on periods when biological activity is possible.

Geographical contrasts underlie fundamental differences in the intensity of seasonality between Antarctic and Arctic regions. The Arctic consists of the northern fringes of large continents surrounding a small ocean, while the Antarctic is a large, permanently frozen continent surrounded by cold ocean. In summer, expanses of Arctic snow-free land absorb solar energy, generating air temperatures 10°C or more greater than those at comparable Antarctic latitudes. This increase in available thermal energy is fundamental to the rate at which biological processes can occur. In contrast, c. 99% of the Antarctic is ice- or snow-covered, with high albedo (reflecting solar energy back into space).

The influence of seasonality on biology can be complex. Antarctic terrestrial and marine environments show fundamental differences even though, in both, many adaptations are interpreted as responses to one or more seasonal features. On land, extreme thermal seasonality restricts biological activity, with further limits being imposed by desiccation, such that activity is possible in some habitats for only a handful of days in a year, or even not at all in specific summers. The intensity of seasonality is modulated by location within the Antarctic: regions close to the coast and with a strong maritime meteorological influence, such as the Antarctic Peninsula and Scotia Arc, experience a climate buffered by proximity to the sea, and receive greater precipitation, than those inland which have a more extreme, continental climate. At the fringes of the Antarctic, the climate of most sub-Antarctic islands is sufficiently buffered to allow the continuation of year-round activity.

While Antarctic marine environments are characterised by extreme physical characteristics (low temperatures, extremes in light, ice, wind speed and disturbance), there is increasing emphasis on the constancy of many aspects, especially that of temperature. Sea temperature fluctuation, as elsewhere, is seasonal, but the annual fluctuation reaches a maximum of only c. 3.5°C west of the Antarctic Peninsula and Scotia Arc islands, and is as little as 0.2°C at sites on the continental Antarctic coast. Rather than temperature, light has the strongest seasonal influence in the Antarctic marine environment, tightly restricting autotrophic production and resource availability for primary consumers, while seasonal ice formation plays a key role in controlling colonisation and structuring communities.

Microphytoplankton (photosynthesising groups >20 μm in size, mainly diatoms) dominate primary production, but are restricted to a 2–3 month summer "bloom." Smaller nanophytoplankton (2–20 μm, mainly ciliates and flagellates) contribute much less biomass but a longer bloom. The smallest group, picoplankton (<2 μm, mainly bacteria), are the least seasonal element. They are unlikely to support macrobiota but are ingested by some and may be important for larvae. Most marine consumers must rely on patterns of primary production, though timings will be offset temporally and may be expanded for benthic suspension and deposit feeders. Thus, resource availability for foragers is thought to be the most important seasonal factor in the thermally stable marine environment. As long as sufficient resources are obtained during their peak period of availability, these biota are not physiologically limited by their thermal environment (as is the case on land) and have more control over the timing of other important biological processes such as somatic growth and reproduction.

PETER CONVEY

See also **Desiccation Tolerance; Microbiology; Phytoplankton; Productivity and Biomass; Temperature**

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SEAWEEDS

In Antarctica seaweeds grow attached to submerged rocky surfaces below the bare zone created by ice scour, which typically extends to 15 m depth. In West Antarctica, large brown algae of the order Desmarestiales dominate the seaweed communities with various smaller, more delicate species forming an understory. At high latitudes in East Antarctica red algae dominate the seaweed communities. The lower limit of seaweeds is probably about 70 m depth. Intertidal species are mostly small filamentous or crustose forms able to survive winter as cryptic, rock-bound stages. In some localities, e. g. on King George Island seaweeds are stranded in large quantities on beaches and support various animal species, in particular nematodes. Even birds use seaweeds as nesting material.

Seaweeds contribute significant amounts of nutrients to Antarctic coastal food webs. Research has shown that in the 2000 m deep King George Basin seaweeds contribute strongly to the total organic carbon pool of the deeper basin waters. Although part of the seaweed biomass in Antarctica is degraded via a detrital pathway, as in temperate regions, physical fragmentation probably plays a more important part in this process than bacterial decomposition.

The Antarctic seaweed flora has a high degree of endemism, and approximately one third of the species is endemic to Antarctica. There are higher levels of endemism in the brown and red algae than in the green algae. In a synopsis of Antarctic seaweeds by Wiencke and Clayton (2002) the number of species was estimated to be around 120–130. With further collections and taxonomic studies, this number will certainly rise in the future.

The Antarctic seaweed flora is characterised by low species richness compared with temperate and tropical regions of the world. Species richness is highest in West Antarctica and decreases dramatically in East Antarctica and at higher latitudes. Few species grow in the Ross Sea and at latitudes above 76° S. The largest nonendemic element of the Antarctic seaweed flora comprises species that also occur on subantarctic islands and Tierra del Fuego. A second group is formed by species that extend to temperate regions of the Southern Hemisphere. Only a few seaweed species have a disjunct, amphiequatorial distribution, occurring both in the Arctic and the Antarctic. Such species probably evolved in one Hemisphere and spread across the equator during a period of lower sea temperatures during the ice ages.

The presently known species number of seaweeds is most likely to be underestimated. Various species known from the temperate region such as the green alga *Enteromorpha intestinalis* were recently collected on Deception Island. They were most likely transported to Antarctica attached as fouling weeds to the hull of ships. Another transport mechanism is through kelp rafting (i.e., the transport of organisms on floating seaweeds). However, this plays a minor role in Antarctica itself, as there is only one species capable of floating through the presence of gas bladders, *Cystosphaera jacquinotii*. This type of transport is much more important in the sub-Antarctic region, where large masses of the brown algae *Macrocystis pyrifera* and *Durvillaea antarctica* support long distance transport with the West Wind Drift around the Antarctic continent.

Most endemic Antarctic seaweeds grow in late winter and spring, although some of them also reproduce in winter. This way they take advantage of the high water transparency in spring and use the incoming light for photosynthesis. Seasonal growth and reproduction in these species is controlled by daylength and intrinsic circannual rhythms. Other Antarctic seaweeds have an opportunistic life strategy and grow predominantly in summer.

Antarctic seaweeds can tolerate dark periods of up to 1 year without suffering damage, and their light requirements for photosynthesis and growth are very low. Many species from the Antarctic only grow (and reproduce) at temperatures below 5°C. The low light demands explain the occurrence of seaweeds down to about 70 m; the low temperature demands determine their northern distribution boundary around the Antarctic convergence.

CHRISTIAN WIENCKE

See also **Benthic Communities in the Southern Ocean; Biological Invasions**

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SEDIMENTS AND PALEOCEANOGRAPHY OF THE SOUTHERN OCEAN

The Southern Ocean was created some 35 million years ago (Ma) when the surrounding continents separated from Antarctica. The sediments accumulating in the Southern Ocean contain the oceanographic history of this basin. The composition of the sediments varies throughout the Southern Ocean and has varied throughout time, governed primarily by the magnitude and type of biological productivity in the overlying water. Remarkably high productivity of diatoms—marine microbes producing opaline shells—is responsible for the Southern Ocean opal belt, a zone of almost pure opal sediments circling the Southern Ocean.

The Southern Ocean was formed during a time of warm global temperatures. As the ice sheets on the Antarctic continent grew, beginning 1 Ma, the Southern Ocean experienced a series of cycles of regular warming and cooling: the Pleistocene glaciations. The circulation, biological productivity, and chemistry of the Southern Ocean were profoundly affected by these changes in climate. Paleoceanographers continue to refine the records of these changes and the tools necessary to interpret them. Moreover, the Southern Ocean does not simply react to climate change; by virtue of its volume, its high latitude, and its communication with all major ocean basins, the Southern Ocean plays a key role in driving and amplifying global climate change.

Surface Sediment Composition

Scientists aboard HMS *Challenger* first noted the major patterns of surface sediments in the Southern Ocean. The most striking feature is the presence of the "opal belt." This band of sediment with high opal (silica derived primarily from the shells of diatoms) content (up to 90%), also called siliceous ooze, is roughly bounded to the north by the Sub-Antarctic Front and to the south by the northern extent of summer sea ice. The existence of the opal belt was once thought to be a paradox: how could sediments rich in opal underlie waters that were traditionally considered to be a biological desert? It was suggested that the preservation of opal is unusually high here relative to other parts of the ocean. Recent work has shown that preservation is in fact typical of global values (Pondaven et al. 2000) and has resolved the paradox by noting that the productivity of diatoms, and in particular their export to the deep sea, is very high in the region overlying the opal belt. Burial of opal in Southern Ocean sediments represents a significant sink in the global oceanic silica cycle. Recent work estimates roughly 45% of all oceanic biogenic silica burial occurs in the Southern Ocean, a downward revision of previous estimates, taking into account the fact that older measures of opal accumulation were too high because of biased coring at sites where sediment was being added by deep ocean currents (DeMaster 2002).

South of the opal belt, where diatom growth is limited by a short growing season, the sediments are primarily composed of silts and clays from Antarctica, including ice rafted debris. North of the opal belt, where growth of diatoms is limited by low silicate concentrations, the ocean floor is covered with either clay or, at depths above the carbonate compensation depth (between 3–4 km, south of the Polar Front), with calcium carbonate. In general, Southern Ocean sediments contain very little calcium carbonate, which presents a problem for paleoceanographers, since many of the common climate proxies are found in biogenic carbonate, such as the shells of single-celled animals called foraminifera. Recently, paleoceanographers have begun to explore the use of opal and diatom-based proxies in the Southern Ocean.

The Tertiary (65–2 Ma)

Much of what is known about the early history of Antarctica and the Southern Ocean has come from cores drilled as part of the Deep-Sea Drilling Project, beginning with leg 26 in 1972. Plate motions positioned the Antarctic continent at high southern latitude since the middle to Late Mesozoic (~150 Ma). During the early Cenozoic the Southern Ocean expanded as plate motions caused the spreading of Australia, New Zealand, and South America from Antarctica. The exact timing of the opening of these seaways is still debated, but clearly by the Eocene-Oligocene boundary (~33 Ma) there was an unrestricted passage for deep water around Antarctica (Kennett et al. 1974). With the opening of this passage, the Antarctic Circumpolar Current (ACC) was formed, and waters were able to flow unimpeded around Antarctica. The ACC is a deep-ocean current that reaches to the ocean bottom and causes dramatic sediment erosion; its development is seen in deep-ocean cores as an abrupt break in sediment deposition. The thermal isolation of Antarctica following the evolution of the ACC during the late Eocene/early Oligocene, coupled with ongoing global cooling induced by declining atmospheric CO_2 levels, led to rapid cooling of Antarctica and eventually to the appearance of Antarctic ice sheets.

There is evidence that a transient but extreme glaciation during the early Oligocene (designated Oi-1) was accompanied by increased fertility of the Southern Ocean, presumably through an intensification of upwelling (Salamy and Zachos 1999). The high rates of carbon burial at this time may have acted as a positive feedback to global cooling, further reducing atmospheric CO_2.

A warming trend in the late Oligocene (27–26 Ma) reduced the extent of the Antarctic ice sheets, and bottom water temperatures gradually rose, reaching a maximum in the Miocene climatic optimum (17–15 Ma). The ice sheets gradually grew back during the late Miocene into the early Pliocene (6 Ma). After a brief period of warmth during the early Pliocene, the Southern Ocean entered a new stage in its climatic history.

The Quaternary (2–0 Ma)

With the appearance of ice sheets in the Northern Hemisphere around 3.2 Ma began a new phase of global, well-documented cycles of waxing and waning of polar ice caps; the Pleistocene glaciations. Cyclical changes in temperature and ice volume, as documented by preserved foraminifera, first appear about 2.5 Ma and continue through the present interglacial period (the Holocene). Several cores from the opal belt in the Atlantic and Indian sectors of the Southern Ocean show 100 thousand-year (denoted 100 Ka) cycles of opal content extending back 450 Ka (Charles et al. 1991). Sediments north of the Polar Front were rich in opal during warm periods and poor during cool periods, while those south of the Polar Front showed the opposite trend. Not surprisingly, the details of Southern Ocean paleoceanography are better known for the more recent glacial cycles particularly the Last Glacial Maximum (LGM $\sim$18 Ka). Reconstructing the biology, chemistry, and physical oceanography of the Southern Ocean during the LGM is a key focus of paleoceanographers studying the region.

Recently there has been much interest in rapid climate change in the Southern Ocean. Cycles of rapid (over 1000 years) warming and cooling (called Dansgaard-Oeschger cycles) were first identified in the Northern Hemisphere ice and deep-sea cores. The Antarctic ice cores also record rapid changes, but their amplitude is smaller and out of phase with those in the northern hemisphere. The few continuous high-resolution records available from Southern Ocean sediments suggest changes in sea surface temperature tracked the climate over Antarctica. There is also evidence from ocean cores that during warm phases of the Dansgaard-Oeschger cycles there was increased delivery of ice rafted debris to the South Atlantic. This is an area of active research.

The following summarizes what is known of Southern Ocean circulation and ocean productivity during the LGM. Included within each section is a brief description of the paleoceanographic tools, or proxies, used to make deductions about past conditions. Proxies, geochemical and paleontological, allow paleoceanographers to indirectly reconstruct past ocean conditions, by making measurements of properties of the sediment that are correlated with the ocean properties to be reconstructed, such as temperature, currents, and nutrient content. In many cases the proxies are open to multiple interpretations. A successful method has been to use many proxies together, each with their own limitations and assumptions, but which together weave a stronger story (multiproxy approach).

Reconstructions of Circulation

Physical oceanographers studying the modern ocean use detailed maps of ocean temperature and salinity, together with other information such as wind strength to deduce the movement of water masses. No such detailed measurements exist from 20,000 years ago, so paleoceanographers use more indirect methods. Several geochemical tracers can be used to “tag” water masses. These include the isotopic composition of dissolved inorganic carbon, $^{13}C/^{12}C$ ($\delta^{13}C$), and the cadmium (Cd) content of the water. They are both roughly correlated with nutrient concentrations. Both of these are incorporated into the shells of foraminifera in proportion to their concentration in seawater. The buried shells are preserved in the sediments and produce a record of past changes in the chemistry of the water at a given location and depth. By combining many such measurements, maps of these distributions are generated that can be used to deduce the movement of water masses. Foraminifera living in the surface (planktonic foraminifera) and at or near the seafloor (benthic foraminifera) document the properties of surface and deep currents, respectively.

In areas of formation of deep water, geochemical gradients in the vertical are minimized due to deep mixing; the similarity between benthic and planktonic $\delta^{13}C$ can then be used to study changes in sites of the formation of deep water (Duplessy et al. 1988).

The densest water mass in the Southern Ocean is Antarctic Bottom Water, which is produced at far southern latitudes and flows northward. This is overlain by Circumpolar Deep Water, which derives from North Atlantic Deep Water (NADW) that flows southward into the Southern Ocean. Mixtures of these two water masses make up the deep water of the world's oceans. The Southern Ocean is a key region in which to examine changes in the global influence of these two water masses. Early evidence based on $\delta^{13}C$ suggested a dramatic reduction of NADW in the Southern Ocean during the LGM. However, Cd records suggested little to no change. Another view is that the water entering the Southern Ocean from the Atlantic was an intermediate water that may then have entered the Pacific via the ACC. Less work has been done to reconstruct the strength of AABW. Several studies, including one based on grain-size analysis and $\delta^{13}C$ find evidence for intensified AABW out the Pacific during glacial periods of the past 1.2 million years. This is still an active area of research, and understanding of the relative strength of the deep water masses evolves as new proxies and new information about existing proxies become available.

The most prominent surface hydrographic features in the Southern Ocean are the fronts of the Antarctic Circumpolar Current. These fronts are areas of strong gradients in temperature, salinity, and in some cases nutrients and ecosystem composition. Some of the earliest studies of Southern Ocean paleoceanography argued for equatorward displacement of the Polar Front during glacial times. These inferences were based on observations that the opal belt was shifted northward during glacial times (Hays et al. 1976) and that front-associated species of foraminifera were also shifted northward. A recent reconstruction of sea surface temperature in the Southern Ocean did not find evidence for such movement, and the current location of the Polar Front is constrained by bottom topography. It thus may have moved less than a few degrees latitude, although a shift might have occurred in biological and chemical features that are today associated with the physical location of the Polar Front.

Reconstructions of Ocean Productivity

One of the great unsolved mysteries of paleoclimatology is the cause of the $\sim$80 parts per million (ppm) lower levels of CO_2 in the atmosphere during glacial times. This pattern appears to be a critical amplifying mechanism, via a reduced greenhouse effect, for sustaining the magnitude of glacial cooling. In the 1980s a number of advances in ocean science led to the proposal of a promising new theory to explain these changes, based on changes in productivity of the Southern Ocean. It was recognized that weak vertical stratification in the Southern Ocean makes it one of the few areas in the ocean where deep water communicates with the atmosphere. Herein lies the possibility for the Southern Ocean to essentially pump CO_2 from the atmosphere into the deep sea (where it is sequestered for about 1000 years) and vice versa. Furthermore, nutrients in the surface waters of the Southern Ocean are currently not completely used by phytoplankton growth. Models suggested that if Southern Ocean phytoplankton were to be 100% efficient in their use of these nutrients then the corresponding uptake of CO_2 during growth could account for the full 80 ppm decrease in CO_2 during glacial times. The recognition that iron limits phytoplankton growth today in much of the Southern Ocean offered a logical mechanism for driving such changes in productivity: increased dust flux during cold periods relieved the phytoplankton of iron limitation and allowed it to make full use of the available nutrients and CO_2.

Evidence consistent with greater iron input to the Southern Ocean during glacial times exists from ocean cores. However, finding conclusive evidence for a glacial increase in the biological productivity of the Southern Ocean has been more difficult. There are essentially two approaches. One can either reconstruct the nutrient concentration of surface waters, which gives direct information on the biological removal of CO_2, or one can reconstruct the rain of biological material to the seafloor (also called the export production). The export production method needs to be coupled with additional information about upwelling intensity, because the net effect on atmospheric CO_2 depends only on the biological consumption of nutrients and CO_2 relative to their supply by upwelling.

The nutrient approach is more direct but has been plagued by problems with interpretation of proxies. The same proxies used to determine the temperature of deep water masses—$\delta^{13}C$ and Cd, among others—can be used to reconstruct nutrient concentrations in surface waters when they are applied to surface-dwelling organisms. A recent reevaluation of the Cd approach (Elderfield and Rickaby 2000), correcting for a temperature bias, finds evidence that during glacial times the consumption of phosphate was less efficient than present day south of the Polar Front and the same as present day north of the Polar Front.

The biological rain, or export production approach, is somewhat less ambiguous, but still open to multiple interpretations. The classic method of using the mass accumulation rate of biogenic material (such as organic carbon or opal) to infer past surface productivity is prone to large errors in the Southern Ocean. This is because strong bottom currents here cause sediment to accumulate in some locations and erode it away from others (Dezileau et al. 2000). The mass accumulation rate can easily be different from the local, vertical rain of material from the surface and might reflect changes in the horizontal supply of sediment from currents. A solution to this problem is to use the naturally occurring radionuclide, ^{230}Th, to obtain an estimate of the flux of material to the seafloor that is corrected for any lateral input (Frank et al. 1999).

The use of these "Th-normalized fluxes" together with other tools including nutrient utilization proxies, has produced a reasonably consistent, if incomplete, picture of qualitative patterns of surface productivity in the Southern Ocean during the LGM. Diatom productivity, and probably all phytoplankton productivity, was almost certainly lower during the LGM than it is today, south of the Polar Front. There is evidence for this in all three sectors of the Southern Ocean (Pacific, Atlantic, and Indian). A reasonable explanation for this is that the greater extent of sea ice during cold periods shortened the growing season and inhibited phytoplankton productivity. Sea ice can be reconstructed by examining the distribution of diatom species. Most reconstructions agree that the winter maximum extent of sea ice was greatly expanded during the LGM. However, the northward extent of sea ice in summer is still not well known. One detailed study suggests summer sea ice extent during the LGM was no different than today (Crosta et al. 1998). North of the Polar Front the records are less clear. In the Atlantic there is evidence for substantially greater diatom productivity and carbon export during the LGM than today. In the Indian sector diatom productivity and carbon export were slightly higher during the LGM than today, and in the Pacific sector preliminary records from a limited number of sites suggest productivity during the LGM was essentially the same as it is today.

A conceptual model to explain these changes has been proposed (Chase et al. 2003). Briefly, if circulation during the LGM were not much different than today, then nutrient-rich waters would continue to upwell south of the Polar Front. If ice cover were substantial there, the consumption of silicate by diatoms, and their export to the seafloor, would have been reduced. The unused silicate would be transported northward. The Atlantic, being closest to continental sources of iron-rich material (e.g., South America), would have received sufficient iron to allow diatoms there to bloom and consume all of the displaced silicate. This can explain the apparent northward migration of the Polar Front. Iron fertilization via dust and continental shelf sediments would be much less in the Pacific, since it is furthest downwind (and downstream) of South America. According to this theory, in the Pacific there was not enough iron for diatoms to use the displaced silica north of the Polar Front. That silica would have been exported northward to the rest of the oceans, where it may have promoted diatom productivity in low latitudes.

ZANNA CHASE

See also **Carbon Cycle; *Challenger* Expedition (1872–1876); Circumpolar Current, Antarctic; Drake Passage, Opening of; Ice Ages; Paleoclimatology; Southern Ocean: Climate Change and Variability; Southern Ocean: Fronts and Frontal Zones**

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SEI WHALE

Sei whales are order Cetacea, suborder Mysticeti (meaning moustache, which refers to baleen plates), family Balaenopteridae, genus and species *Balaenoptera borealis* (Lesson 1828). The name *borealis* means "northern," reflecting the fact that it was first known from the northern North Atlantic. Other common names used in the past include coalfish whale and pollock whale. The name "sei" is derived from its tendency to arrive in Norwegian waters at the same time as the *seje,* the Norwegian name for the saithe otherwise known as the coalfish or pollock *(Pollochius virens)*.

General Appearance and Size

Sei whales are the third largest of the balaenopterids. In the Southern Hemisphere, they average about 15–16 m in length and weigh around 20 tonnes. Females are generally about 5% longer than males. The largest animals can reach up to 20 m.

The slender sei whale is perhaps the most streamlined of all the whales. Its narrow head has a single well-defined head ridge running to the paired blowholes. Its closest relative, the Bryde's whale *(B. edeni)* is characterised by three head ridges. The dorsal surface of the sei whale is generally dark grey in colour. The skin shows little mottling (although it is sometimes covered in pale oval scars thought to be caused by lampreys or remoras). The ventral surface is paler. The dorsal fin is relatively tall (0.25–0.75 m) and generally falcate. It is set about two-thirds of the way along the back. Sei whales are rorquals and have 38–65 ventral grooves that run from the lower jaw and end well before the umbilicus, unlike in the blue *(B. musculus)* and fin *(B. physalus)* whales; these grooves allow the mouth to expand when feeding. They have about 350 relatively narrow, black, triangular baleen plates hanging from the upper jaw on each side (about 0.8 m in length and 0.3 m at the widest part) spaced 1–3 cm apart, used in filtering food from the water. The bristles are much finer than those for the blue and fin whales. The flippers reach about 10% of body length and are dark grey on top and paler underneath, as are the broad flukes.

In Antarctic waters, all or portions of the body may have a dark yellow-green to brown sheen from the presence of diatoms.

Distribution and Migration

Sei whales are found throughout the Southern Hemisphere (and indeed, the Northern Hemisphere). They migrate between subtropical breeding areas (although the location of the breeding grounds is unknown) and their Antarctic feeding grounds, which appear to be related to the Polar Front; most sei whales being found around the Polar Front north of about 55° S. Like the other large whales, sei whales rarely feed outside the Antarctic and so in the 4 months (December to March) they are in the Antarctic they must store energy in their blubber to last them for the migration to and from the breeding grounds. Although detailed information on stock structure is lacking, there are probably at least six separate populations of sei whales in the Southern Hemisphere.

Life History and Behaviour

Sei whales are thought to live up to 40–50 years old. They reach sexual maturity at around 14 m (females) and 13 m (males) when they are about 8–10 years old. The gestation period is thought to be around 11–12 months; new born calves measure around 4.5 m. They are weaned at about 6 months, by which time they have reached about 8 m. There is some evidence that pregnancy rates increased and animals reached sexual maturity earlier as a result of whaling, perhaps as more food per individual became available.

Little is known about the social structure of sei whales. They are usually seen as single animals or in small groups, although larger concentrations are known in areas of high prey density. Sei whales feed on a wider range of species than the other rorquals, primarily the Euphausiid *(E. vallentini)* but also copepods (e.g., *Calanus tonsus*) and amphipods (e.g., *Parathemisto gaudichaudii*).

Unlike other balaenopterids, which can be classified as "gulpers," sei whales often skim feed somewhat like right whales *(Eubalaena australis)*. It has been postulated that this method of feeding allows them to exploit less dense patches of prey. Sei whales are the fastest swimming whales with normal travelling speeds of around 6–7 knots with short bursts of as much as 20–25 knots occurring if chased.

Conservation/Status

Sei whales became a serious target of commercial whaling in the Antarctic only after blue whales and fin whales had been heavily depleted. About 179,000 were killed south of 40° S between 1905 and 1977, with over 65% of these being killed between 1964 and 1972. They have been protected by the International Whaling Commission in the Southern Hemisphere since 1978.

There are no good estimates of the abundance of sei whales in the Southern Hemisphere before they were exploited. Some scientists have suggested that sei whales may have begun to increase in numbers prior to their heavy exploitation as a result of the decrease in numbers of blue and fin whales, but it is not possible to test this theory. Similarly, there are no recent estimates of abundance. The reason for the latter is that most abundance surveys occur south of 60° S.

Aside from man, the only likely predator of sei whales is the killer whale, *Orcinus orca,* although there are no documented reports of attacks. The effect of climate change on stocks of krill and other sei whale prey species is unknown.

ROB WILLIAMS

See also **Blue Whale; Copepods; Diving—Marine Mammals; Fin Whale; International Whaling Commission (IWC); Killer Whale; Polar Front; Whales: Overview; Whaling, History of**

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SHACKLETON, ERNEST

Ernest Henry Shackleton (February 15, 1874–January 5, 1922) was the most charismatic of all Antarctic explorers and is best remembered for rescuing his party from the Weddell Sea after their ship *Endurance* had been crushed by ice. The qualities he displayed during that trying time have made him a paradigm for modern leadership skills. The *Endurance* story has overshadowed his other achievements and obscured his failings in organisation and business aptitude.

Shackleton was born in Kilkea, County Kildare, Ireland, and the family moved to south London when he was 10. He was educated at Dulwich College until the age of 16, when he signed on the square-rigger *Hoghton Tower* as a ship's boy. After 11 years of working his way up the promotion ladder, his last voyage as a merchant seaman was as third officer on the liner *Carisbrooke Castle*.

It appears that Shackleton was attracted to join the British National Antarctic Expedition (1901–1904) both for adventure and as a means of improving his financial prospects. By making use of intermediary contacts, Shackleton was appointed third officer on the expedition ship *Discovery*. Robert Falcon Scott's decision that *Discovery* would winter in Antarctica allowed Shackleton to participate fully in the land-based activities of the expedition. He made the second balloon ascent in Antarctica and took the first aerial photographs. He led the first overland journey, which lasted four days and showed how ill-prepared the expedition was for Antarctic travel. From the beginning, Shackleton had difficulty mastering the use of skis and dogs; failings that most likely later cost him the South Pole and might have jeopardised the crossing of Antarctica.

The next summer, Shackleton accompanied Scott and Edward Wilson on the major southward journey. All three men suffered from scurvy, and Shackleton was invalided home as unfit for further duty. On this expedition, Shackleton was already showing his enthusiasm, drive, and ability to win the admiration of his fellows.

Shackleton benefited from being the first officer to return from Antarctica, because he made a name for himself through lectures, articles in the press, and by forming personal contacts. He became Secretary to the Royal Scottish Geographical Society but resigned within the year to stand, unsuccessfully, as a candidate for Member of Parliament for Dundee in the 1904 General Election. He also married Emily Dorman, and they had the first two of their three children, Raymond and Cecily. (Shackleton's youngest child, Edward, would later become Lord Shackleton.)

During this period Shackleton was employed by William Beardmore, a Clydeside ship builder. On February 11, 1907, he announced his plans for the British Antarctic Expedition, the primary objective of which was to reach the South Pole. He then discovered that Scott was planning a second expedition with the same aim. Shackleton signed an undertaking with Scott not to land in McMurdo Sound and use the *Discovery* base. He tried to set up base at the other end of the Great Ice Barrier (now known as the Ross Ice Shelf), but he could not find a suitable landing place and reluctantly established his base at Cape Royds, not many miles from Scott's old base at Hut Point. He was later severely criticised for this decision.

Shackleton, with Frank Wild, Jameson Adams, and Eric Marshall, reached 88°23′ S, before being forced back by shortage of food. This was arguably the most important attempt on the Pole because it revealed that the Pole lay on a high, ice-covered plateau. Covering the final 97 geographical miles (112 statute miles or 180 km) to the Pole would not have added significantly to geographical knowledge. The expedition also reached the South Magnetic Pole and made the first ascent of Mount Erebus.

The expedition returned to great popular enthusiasm in Britain, and Shackleton was knighted. However, the expedition was seriously in debt. It was aided by a large government grant but the financial situation was not helped by Shackleton's habit of donating to charities funds raised by lectures and public exhibitions on the expedition ship *Nimrod,* even though he still owed expedition members their salaries. Shackleton also had to combat allegations, from Sir Clements Markham among others, that calculation of latitudes by his navigator, Marshall, had been faulty.

In 1911, Amundsen and Scott reached the South Pole, with Shackleton watching from the sidelines. During this period, he gave advice to the Argentines on the relief of Otto Nordenskjøld's Swedish South Polar Expedition. On December 29, 1913, Shackleton publicly announced The Imperial Trans-Antarctic Expedition in a letter to *The Times*. The aim was to cross the continent via the South Pole from the Weddell Sea while other parties explored to the base of the Antarctic Peninsula and the coast of Enderby Land. Another party was to land at McMurdo Sound and lay depots for the crossing party.

The expedition set sail in August 1914, as war was declared. It was delayed at South Georgia because of the late dispersal of ice in the Weddell Sea and was eventually trapped in pack ice not far from the proposed landing site at Vahsel Bay. Having weathered the disappointment of failure of his plans and survived the months of wintering on board, Shackleton's leadership skills were tested to the utmost when *Endurance* was crushed and the ship's complement took to the ice. It soon proved that there was little the men could do to help themselves by travelling over the ice, and they had to wait while they drifted northward toward open water. The subsequent journey in three small boats to Elephant Island, the voyage to South Georgia in *James Caird,* and the crossing of South Georgia form the basis of Shackleton's reputation as a leader. Extreme courage and the ability to maintain the morale of his men were paramount.

Following the rescue of the Ross Sea Party and his return to Britain, Shackleton attempted to find military work, although he was too old to be required to join the armed forces. He was eventually sent, unpaid, to Buenos Aires to spread British propaganda but was recalled 5 months later and attached as winter-equipment officer to an expeditionary force sent to Murmansk, Russia. With him went Worsley, Hussey, Macklin, and Stenhouse from the Imperial Trans-Antarctic Expedition. After the war he planned an expedition to look for new lands in the Arctic but, when the Canadian government withdrew support, he headed south aboard *Quest* on the Shackleton-Rowett Expedition and died on reaching South Georgia.

Shackleton's reputation was for a long time eclipsed by Scott's, but there was a remarkable revival in the 1990s, in what the *New Yorker* called "Shackleton-mania." Shackleton is sometimes said not to have achieved any of his objectives, but this obscures the importance of his achievements on the *Nimrod* expedition. His fame, however, depends on his qualities of leadership and endurance when rescuing his men from the Weddell Sea, rather than his success as an explorer. Despite ill health (he refused to let doctors examine him), he undertook incredible feats of endurance, such as the return from the attempt on the South Pole and the crossing of South Georgia. As a leader, he emphasised care for his men and easy communication, and he always extolled group efforts. To quote Percy Blackborow of the Imperial Trans-Antarctic Expedition: "He had a genius for keeping men in good spirits and, need I say more—we loved him as a father."

Robert Burton

See also **British Antarctic *(Nimrod)* Expedition (1907–1909); British National Antarctic *(Discovery)* Expedition (1901–1904); Imperial Trans-Antarctic Expedition (1914–1917); Markham, Clements; Ross Sea Party,**

Imperial Trans-Antarctic Expedition (1914–1917); Scott, Robert Falcon; Shackleton-Rowett Antarctic Expedition (1921–1922); South Pole; Swedish South Polar Expedition, Relief Expeditions; Worsley, Frank

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SHACKLETON RANGE

The Shackleton Range is situated between 80° S and 81° S, and 31° W and 19° W in the Atlantic continuation of the Transantarctic Mountains, sometimes included, mostly not. It extends 200 km from east to west with a width of 80 km from north to south. It was first visited during the Commonwealth Trans-Antarctic Expedition (1955–1958) and studied by British expeditions in 1967, 1968–1971, 1977–1978, by Soviet expeditions in 1976–1977 and 1978–1979 (including German geologists from the former DDR), by a German Expedition (GEISHA: 1987–1988), and by a European Expedition (EUROSHACK 1994–1995).

The Shackleton Range forms a key area for all concepts concerning the geological architecture of Antarctica and even Gondwana. Firstly, its main phase of deformation and metamorphism is dated at about 500 Ma (Pankhurst et al. 1995; Tessensohn et al. 1999) and is therefore directly related to the formation of Gondwana. Secondly, its internal grain is oriented nearly orthogonal to Gondwana's paleo-Pacific margin, corresponding in Antarctica to the c. 500 Ma old Ross Orogen of the Transantarctic Mountains.

From the paleo-Pacific margin the range extends eastward and then disappears under the extensive and thick ice cover of southern Dronning Maud Land, which traditionally was attributed to the East Antarctic Craton (e.g., James and Tingey 1983). In spite of their contemporaneity, the main orogenic processes are fundamentally different in the Ross Orogen proper in the Transantarctic Mountains on the one hand and in the Shackleton Range on the other hand. Predominantly subduction-related processes in the former contrast with predominantly collision-related processes in the latter (Tessensohn et al. 1999). One of the most relevant results is the discovery of an ophiolitic complex traceable for more than 100 km, the oceanic past of which must have been in the period between 1000 and 500 Ma (Talarico Kleinschmidt, and Henjes-Kunst 1999) (i.e., the right time and the right place for having formed part of the Moçambique Ocean that separated East and West Gondwana before final amalgamation of the supercontinent in late Pan-African times).

A Simplified Tectono-Stratigraphic Column from Top to Bottom.

Permo-Carboniferous glacial deposits (Tessensohn, Kleinschmidt, and Buggisch 1999; see also Beacon Supergroup)	*very eastern end of central strip*
Blaiklock Glacier Group (Ordovician molasse)	*western end of northern and central strips*
- - - unconformity - - -	
Pioneers Group (mainly medium-grade metamorphic "supracrustals," including the ophiolite)	*northern and central strip (ophiolite: northern strip)*
- - - mainly thrust contact - - -	
Stratton Group (high-grade metamorphic basement)	*northern and central strip*
- - - main thrust - - -	
Mt. Wegener Nappe • Mt. Wegener Formation (Cambrian flysch) • Wyeth Heights Formation • Stephenson Bastion Formation.	*(all formations consist of low-grade metamorphic rocks; southern strip plus four tectonic windows in the central strip)*
- - - main thrust - - -	
Watts Needle Formation (epicratonic, autochthonous Eocambrian sediments: soil, arkose, sandstone, limestone, shale)	*southern strip*
- - - unconformity - - -	
Read Group (high-grade metamorphic basement of the East Antarctic Craton)	*southern strip*

The Shackleton Range consists mainly of three rock complexes:

1. Relatively low-grade metasediments.
2. A large variety of medium- to high-grade metamorphic rocks (including ophiolites).
3. A cover of molasses-like sediments, the Ordovician Blaiklock Glacier Group.

These rock types can be attributed to three east–west running topographic units (strips) of the range: a northern strip dominated by the Lagrange Nunataks and the Herbert Mountains, a central strip largely covered by ice (Fuchs Dome, Shotton Snowfield), and the southern strip dominated by the Read Mountains.

There is a large and confusing number of stratigraphic terms, some of which are unnecessary and obsolete (see Clarkson et al. 1995). A simplified tectono-stratigraphic column from top to bottom is shown in the table.

The structural characteristic of the Shackleton Range is a large-scale nappe tectonics, as indicated in the tectono-stratigraphic column. Nappe tectonics has already been assumed by Marsh (1983). Nappe tectonics of Pan-African age concerning the Mount Wegener Nappe in the Read Mountains was firstly proven by Buggisch et al. (1990, 1994) and confirmed by additional evidence throughout the southern strip (Buggisch and Kleinschmidt 1999). That nappe tectonics dominate the entire structure of the Shackleton Range with the formation of several tectonic windows, was shown by Kleinschmidt et al. (2001). The tectonic transport directions change systematically: it is southward directed in the south, westward directed in the north, and south-westward in between (Kleinschmidt et al. 2002). Compressional tectonics is overprinted by late to post-tectonic collapse producing abundant low-angle normal faults and kink bands with dip-slip displacement (Kleinschmidt and Brommer 1997).

GEORG KLEINSCHMIDT

See also **Beacon Supergroup; Commonwealth Trans-Antarctic Expedition (1955–1958); Geological Evolution and Structure of Antarctica; Gondwana; Transantarctic Mountains, Geology of**

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SHACKLETON-ROWETT ANTARCTIC EXPEDITION (1921–1922)

After the end of World War I, Sir Ernest Shackleton planned an expedition to search for new lands in the Arctic. Thinking he had obtained the backing of the

Canadian government, he bought a 125-ton sealing vessel, *Foca I,* and recruited some members of the Imperial Trans-Antarctic Expedition. However, the Canadian government withdrew its support, and Shackleton decided to head for Antarctica instead. John Quiller Rowett, who had known Shackleton when they were pupils at Dulwich College, agreed to underwrite the expedition, which was named the Shackleton-Rowett Antarctic Expedition.

Shackleton's new proposal for an "oceanographical and sub-Antarctic expedition" was exceedingly ambitious. The expedition vessel would be called *The Research* and it would visit the South Pacific as well as Antarctica. Geographical research would include searching for doubtful and badly located islands and rocks and filling in 2000 miles (3200 km) of Antarctic coastline, from Enderby Land to Coats Land. There would be comprehensive projects on meteorology, geology, mineralogy, earth magnetism, botany, marine biology, and anthropology. There would be an emphasis on economic aspects, such as searching for precious metals, phosphates, wolfram, iodine-rich kelps, and sealing and whaling grounds. The expedition would also "ascertain, once and for all the history and methods of the Pacific natives in their navigation across Pacific spaces." Shackleton also planned to make the first use of an aircraft in Antarctica and, according to one account, even proposed flying to the South Pole. The reality was very different.

The nucleus of the expedition was the "old guard" from *Endurance:* Frank Wild, Frank Worsley, Alexander Macklin, James McIlroy, Leonard Hussey, Alfred J. Kerr, Thomas McLeod, and Charles Green. Other members included James Marr, a Boy Scout who was chosen from 1700 applicants and who later became a leading Antarctic marine biologist, and the Australian Hubert Wilkins, who later became the first man to fly in Antarctica.

The expedition was made ready in 3 months. *Foca I,* renamed *Quest,* was modified with the addition of a deckhouse for accommodation and an enclosed bridge, and sailed from London on September 17, 1921. St. Paul's Rocks were visited, but there were also several unscheduled stops to repair the engine, and four weeks was spent on a major refit at Rio de Janeiro. It was now too late to proceed to Cape Town, where the aircraft—an Avro "Baby" seaplane—and many stores were waiting, so a course was set for South Georgia. *Quest* rode out a huge storm for 4 days and developed a leaking boiler before reaching the shelter of Grytviken and the company of old friends among the whalers, on January 4, 1922. They also met up with Wilkins and Vibert Douglas, who had travelled ahead from Rio de Janeiro to undertake scientific work (natural history and geology, respectively) on South Georgia.

That night Shackleton suffered a heart attack and died. The shocked crew took his body ashore at Grytviken where a postmortem revealed longstanding heart disease. Wild, who took over as leader, decided to send Shackleton's body to England for burial, accompanied by Hussey. Meanwhile the expedition would continue, but as many of the men had joined Shackleton rather than the expedition, the expedition had lost much of its *raison d'être*.

Shackleton had discussed two plans with Wild. One was to penetrate the pack ice and reach Enderby Land and survey the coastline, but Wild considered this too dangerous with the poor state of *Quest*. The alternative was to overwinter on the western coast of Graham Land (now the Antarctic Peninsula) and travel overland to the Weddell Sea in the following season. This plan had to be rejected because the specialist clothing, food, and dogs left at South Georgia by Wilhelm Filchner's *Deutschland* expedition, which Shackleton had hoped would replace the stores left at Cape Town, were no longer available.

After fuel and stores had been obtained from the whaling stations, they sailed from South Georgia on January 18 with the aim of penetrating the Weddell Sea and proceeding along the southern coast. *Quest* headed south via the South Sandwich Islands, where a running survey was made of Zavodovski Island and soundings taken. Bouvetøya had to be missed through lack of time, but they altered course to search for Pagoda Rock, which had been reported in 1845. There was no sign of it, as it had probably been a large iceberg. Heavy ice now thwarted their progress into the Weddell Sea, and they were forced to turn back at 69°17′ S, 17°9′ E. On the way north, James Clark Ross's "Appearance of Land" was investigated, but, although ice prevented reaching the precise spot, there was no sign of land and a sounding nearby gave a depth of 2331 fathoms.

Skirting westward along the ice edge, *Quest* reached Elephant Island, where a number of the crew had been forced to stay in 1916. Landings were made at Cape Lookout and Minstrel Bay to collect seal blubber for eking out the meager supplies of coal, but deteriorating weather prevented a landing at Point Wild and deprived McIlroy of the chance to retrieve the diary he left there in 1916. With another gale blowing up and causing considerable damage, together with the serious shortage of coal, Wild turned *Quest* toward South Georgia.

On April 16, *Quest* reached Leith Harbour whaling station, where the crew was surprised to find Hussey. He told them how he had brought Shackleton's body back to South Georgia for burial at Grytviken.

For two weeks *Quest* lay at Leith Harbour and Stromness while storm damage was made good. Prince Olav Harbour was visited for coal, and soundings were made around the northwest end of South Georgia. On April 2, *Quest* left for Grytviken, where the crew constructed a memorial cairn and cross for Shackleton at Hope Point and the men from *Endurance* visited Shackleton's grave to say farewell to "The Boss."

Following a visit to Royal Bay, where the station of the German Transit of Venus expedition was inspected and more soundings made, *Quest* headed for Tristan da Cunha. On their arrival on May 19, they found the islanders in a fairly destitute state and gave them what they could spare of stores and food. Visits to Nightingale, Inaccessible, and Middle islands were followed by a week at Gough Island. Cape Town was reached on June 18, and *Quest* left on July 13 for the long run up the Atlantic. Calls were made at Ascension Island, St. Helena, St. Vincent, and the Azores. On September 16, 1922, *Quest* finally anchored at Plymouth, one year after it had left England.

The Shackleton-Rowett Expedition is remembered for the untimely death of its leader. The proposed program was ambitious but vague, and the small, underpowered, unseaworthy *Quest* was lucky to survive the voyage to the Antarctic and back. Despite the limitations of an inadequate vessel and the loss of its leader, the expedition persevered and made some useful contributions to the knowledge of little-known places in the South Atlantic.

ROBERT BURTON

See also **German South Polar *(Deutschland)* Expedition (1911–1912); Imperial Trans-Antarctic Expedition (1914–1917); Marr, James; Shackleton, Ernest; South Georgia; Wild, Frank; Wilkins, Hubert; Worsley, Frank**

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SHEARWATERS, SHORT-TAILED AND SOOTY

The short-tailed shearwater, *Puffinus tenuirostris,* and sooty shearwater *P. griseus,* represent two of the nineteen medium-sized petrels in the genus *Puffinus*. The sooty is slightly larger than the short-tailed shearwater, ranging between 650–980 g and 480–800 g, respectively. Both species are all dark above except the sooty shearwater is identified by having more white in the area of primary coverts. The phylogenetic history is little known for either species. Most of the modern species-groups, or subgenera, of *Puffinus* were in existence by the Middle Miocene, and there has been very little morphological change within these lineages in 15 million years or so. Fossil remains suggest that the short-tailed shearwater and its congeners were differentiated in the North Atlantic Ocean–North America regions. On mainland Australia, Tasmania, and New Zealand, the earliest short-tailed and sooty shearwater remains are from coastal deposits of the late Pleistocene or Holocene. Having settled in the Southern Hemisphere, the post-breeding migration of the short-tailed and sooty shearwaters may be an instinctive response to return to their ancestral "home."

Like most seabirds, the two species spend 90%–95% of their life at sea, ranging to the Antarctic Circle in the breeding season and migrating to the North Pacific Ocean in the nonbreeding season, with a small proportion of birds remaining in home waters all year round. South American populations of sooty shearwaters also migrate to the North Atlantic Ocean. In terms of numbers and biomass, the short-tailed shearwater is the dominant seabird around the Aleutian Islands and Bering and Chukchi seas. The sooty shearwater is most abundant over the deep-water basin of the central Pacific Ocean, and along the west coast of North America. The northern water masses are richer in food than subtropical waters, and it is likely that both species pass relatively quickly across these transitional regions without pausing to forage.

Shearwaters make landfall at the breeding colonies at the end of September. Their breeding timetable is highly synchronised to the extent that it was once thought all birds laid on the same day (which is close to the truth, because 85% of all eggs are laid within 3 days either side of 24–25 November). Eggs are incubated for 54 days, and the chicks fledge approximately 100 days after hatching. The chick receives its last meal about 10 April, enters a "starvation period," and fledges 2–3 weeks later in late April to early May. Long-term research of more than 55 years on the short-tailed shearwater reveals that they first breed between 4 and 15 years of age, and can live up to 38 years. On average, male shearwaters live for 9.2 years and females for 9.4 years after commencing breeding. Reproductive success at first increases with age but then decreases as birds become older, and overall, 8% of breeding shearwaters produce 53% of all young returning to breed. In the last years of their breeding life, shearwaters tend to change mates and burrows, miss years and form associations that do not result in reproduction.

The short-tailed and sooty shearwaters are two of the most aquatic of the *Puffinus* genus, having a long narrow pelvis, compressed tarsus, well developed knee joint process, a long sternum, short thick compressed humerus and a short smooth body plumage. During daily foraging trips, they are capable of making regular and almost continuous dives to 60 m for several successive hours. At night, they spend most of their time floating at the water surface. They feed, in successive order of importance, by pursuit plunging, surface seizing, pursuit diving, scavenging, hydroplaning, and bottom feeding. During the breeding season, shearwaters forage over vast areas of the southern temperate, sub-Antarctic and Antarctic biogeographical sea zones, with sooty shearwaters more abundant in both the sub-Antarctic and Antarctic zones.

During the chick-rearing phase, parent birds maintain themselves in highly productive areas in the subantarctic and Antarctic zones, located vast distances from breeding colonies, and provision chicks from local sources. A cyclic pattern results of two or three short trips of 1–2 days duration followed by a long foraging trip of 8–13 or more days. Capable of flying 1000 km per day at speeds of up to 58 km per hour, a parent bird consumes food equivalent to 40% of its body mass daily in order to meet its own and the nestling's energy needs. The Antarctic zone is very rich in phytoplankton, and productivity is enormous during the short Antarctic summer, with krill, specifically *Euphausia superba* the most frequent food taken. In the southern temperate zone, the main food items are krill such as *Nyctiphanes australis,* squid, fish and crustaceans with the diet changing in response to the seasonal abundance and distribution of prey species.

Both shearwater species are very abundant, and one of the main reasons postulated is that where prey densities are high enough to render underwater pursuit viable, both species essentially forage in three dimensions. Feeding offshore and underwater opens more areas to locate food. The short-tailed shearwater only breeds in southern Australia with an estimated population of 23 million adults. Tasmania contains 80% of total population with approximately 9 million pairs in 211 colonies covering 1813 ha. The largest colony is Babel Island in Bass Strait with 2.86 million burrows. The sooty shearwater has a much wider distribution. In New Zealand, colonies centre on islands lying south of South Island. The largest population is 2.01 million burrows on the Snares Islands, 105 km south of Stewart Island (Rakiura). Colonies in southeastern Australia total several thousand pairs. Numerous colonies also occur on the eastern side of the South Pacific Ocean in southern Chile, Argentina and on the Falkland Islands, which may number several million birds. The estimated total population for all regions may be 20 million birds. There are no major genetic differences between the New Zealand and Chilean populations, suggesting mixing among colonies. It also breeds in very small numbers on Tristan da Cunha.

Mortality is mainly due to starvation, predation, and human activities. In New Zealand sooty shearwater numbers have decreased by up to 54% in the past 50 years. Historically, they bred all around New Zealand but most mainland colonies are functionally extirpated due to predation, mainly by introduced mustelids and habitat loss. Off the coast of California, sooty shearwater numbers have decreased by 90% since the late 1980s. Climate change has been implicated with links to a corresponding decrease in abundance of zooplankton, rather than simply a distributional shift in feeding location and change in migration route. No similar population changes have been detected in short-tailed shearwaters, but the recent deliberate introduction to Tasmania of red fox *Vulpes vulpes* is a major cause of concern. Large episodic mortality does occasionally occur, however, during termination of transequatorial migrations due to food shortages brought about by anomalous weather events. Shearwaters in good body condition have the capacity to fly approximately 8300 km before succumbing to starvation. The great circle distance between New South Wales and the far North Pacific Ocean is approximately 9500 km, so if food is unavailable en route large mortalities could result, but the impact on the population is largely unknown.

Human impacts include harvesting or "muttonbirding" of short-tailed shearwaters in Tasmania and of sooty shearwaters in New Zealand. Both species are commonly known as "muttonbird," a term coined in 1790 when wedge-tailed shearwaters *P. pacificus* were consumed by convicts to supplement food on Norfolk Island in the central Pacific Ocean. Then, they were described as remarkably fat with the taste resembling that of sheep or mutton. Because of the birds' high nesting densities and site fidelity, the short-tailed and sooty shearwaters are highly vulnerable to exploitation. Present-day harvesting takes up to several hundred thousand chicks annually in both these countries.

Shearwaters in particular ingest more plastic than any other seabird group recorded to date. Chlorinated hydrocarbons, including dioxin and heavy metals, have been detected in shearwaters at breeding grounds and on their migration routes. Oil spills are another irregular hazard. North Pacific Ocean driftnet fisheries for salmon and squid previously caused the largest bycatch of sooty and short-tailed shearwaters of all seabirds. The United Nations ban on pelagic driftnet fishing on high seas in 1992 removed some of this risk, but the high mortalities caused by these fisheries in the past may have had long-term effects on the demographics of these two long-lived shearwaters.

The short-tailed and sooty shearwaters occur in seemingly high numbers and have long breeding lives but are vulnerable to many outside factors. Monitoring programs and management decisions that are based on best available data are required to ensure the two species survive into the future.

IRYNEJ SKIRA

See also **Birds: Diving Physiology; Fish: Overview; Phytoplankton; Seabird Conservation; Seabird Populations and Trends; Seabirds at Sea; Squid; Zooplankton and Krill**

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SHEATHBILLS

There are two varieties of sheathbill: the black-faced sheathbill *(Chionis minor)* and the pale-faced sheathbill *(C. alba)*. It belongs to the order Charadriiformes.

The body length of the sheathbill is 34–41 cm, and its body mass is 450–750 g. Males are generally larger than females. Size varies among the different subspecies of *C. minor, C. m. minor,* and *C. m. nasicornis* being the largest. The plumage is entirely white; the animal is also marked by a stout conical bill, strong legs, and unwebbed feet. It has a gait recalling both the pigeon and domestic fowl. Sheathbills typically walk and can run fast but are usually reluctant to fly. In flight, sheathbills display broad wings and fast wingbeats.

The *C. alba* has dark grey legs, pale pinkish facial caruncles, a yellowish-horn bill and a greenish-yellowish-horn sheath (but bill tip and ridge on upper mandible are brownish). Among *C. minor,* leg colour varies among subspecies, from pink to blackish. It displays black caruncles on lores and sides of upper mandible (also at the base of lower mandible and on chin in *crozettensis* and *marionensis,* which also have a small head crest), a black bill, and a slaty blackish grey sheath. Both species have a pink orbital circle, a brown iris, black claws, and a black, blunt, carpal spur (sometimes two in *C. m. crozettensis*). Juveniles have very small or no caruncles, no head crest, and a less prominent sheath, and they utter feeble, shrill, and cheeping calls, contrasting with the strong stacatto calls of adults.

General Description of Population Status

The sheathbill is not globally threatened. *C. alba* is monotypic and occurs from Antarctic Peninsula to 34° S; its estimated population is about 10,000 pairs. *C. minor* is present at only four sub-Antarctic localities in the Indian Ocean, each locality holding an endemic subspecies: Prince Edward Islands (*marionensis,* c. 4300 individuals, including 1400 pairs) where the population is decreasing due to competition for food (terrestrial invertebrates) with introduced mice *Mus musculus* during the winter; Îles Crozet (*crozettensis,* 1000 pairs); Îles Kerguelen (*minor,* 3000–6000 pairs), and Heard Island (*nasicornis,* estimated 1000 pairs). Population estimates at the latter three localities lack any accuracy. The sheathbill's habitats include shores, especially seabird (penguin and cormorant) colonies, occasionally southern elephant seal *Mirounga leonina* colonies when females give birth to their pups; they do not generally venture far inland. Sheathbills cannot breed without access to a seabird colony, except at Îles Kerguelen where the presence of an extensive intertidal zone on some islands provides pairs with sufficient alternative food.

Life History

C. alba breeds from South Georgia to the Antarctic Peninsula. The northernmost populations are sedentary, whereas the southernmost ones migrate as far as Patagonia and the Falklands. *C. minor* is sedentary.

At Îles Crozet and Prince Edward Islands, however, many individuals breed among crested penguins *Eudyptes* spp. and move to king penguin *Aptenodytes patagonicus* colonies (where food availability is highest and most predictable) in winter, whereas those breeding among king penguins maintain their territories throughout the year. At Îles Kerguelen, many pairs, including those breeding on seabird-free territories, remain on their territory all year, but some individuals can wander a few tens of kilometers. In both species, laying occurs from early to mid-December until mid-January. Nests are situated under rocky boulders, in caves, crevices, sometimes in abandoned petrel and rabbit burrows (where present), or under human settlements. Clutch size is one to four or five eggs, usually two to three. Eggs are a pale creamy-brown color, with irregular dark brown or olive brown blotches. Incubation is 27–32 days, starting with first egg. Asynchronous hatching takes place. Chicks are semi-precocial, nidicolous, and hatch with mottled brownish down, replaced by dark grey mesoptile at 14 days; they are fully feathered by 7–8 weeks. Chicks of *C. minor* are almost continuously brooded by the parents during the first 2 weeks. Chicks are fledging at 50–70 days, but young often fed by parents for several more weeks. The age at first breeding is 3–7 years *(C. minor)*, breeding attempts at 3 years being scarce and often unsuccessful. Survival rates are as follows: *C. alba*: out of seventy-three adults banded at Signy Island, sixty-six returned the next year. *C. minor* has a high adult annual survival (Prince Edward Island: 0.88, Îles Crozet: 0.85, Kerguelen: 0.894 between 1989 and 2002). Maximum longevity is at least 19 years *(C. minor)*. Breeding frequency is one clutch per year. Replacement clutches may occur on the Prince Edward Islands. When considering individual *C. m. minor* monitored for at least 5 years after their first known breeding attempt, 77% of the breeders in year n that survive until year $n + 1$ will breed in year $n + 1$ (fifty-eight individuals monitored between 1989 and 2002).

Social Structure (Breeding Behaviour, Group Structure)

Sheathbills form long-term, monogamous pair bonds. One female-female pair was observed at Îles Kerguelen. The maximum known pair bond duration is 12 years, observed at Îles Kerguelen. The divorce rate at Îles Kerguelen between 1988–1989 and 2001–2002 was 6.7%, or 15 out of 224 pairs; at Îles Crozet between 1978–1979 and 1987–1988, the rate was 2.4%, or 2 out of 82 pairs; divorce was not observed on Marion Island. Both genders can initiate divorce. Pair mates share parental duties during incubation and chick-rearing. Adults carry food in their bills to chicks, walking from the feeding area to the nest.

Each pair has its territory in which mates breed and, generally, feed. Strong territorial behaviour is associated with intense competition for territories. Îles Kerguelen is the only locality where nonbreeders can possess a territory. Sheathbills exhibit a high year-to-year territory fidelity (87.1% at Kerguelen, n = 550 adult individuals). In king penguin *Aptenodytes patagonicus* colonies, nonbreeders can form groups of "floaters." The social structure is related to food availability and quality in winter, when large flocks can be observed. A great variety of agonistic displays occur.

Diet and Trophic Interactions

Sheathbills forage mostly diurnally, among kleptoparasiting seabirds when the latter are feeding their chicks, to obtain fish and crustaceans, and entering burrows of large petrel species to take their eggs and small chicks. Sheathbills also feed on invertebrates, carrion, faeces, placentae, blood, human wastes, and the milk of female elephant seals when the latter are suckling their pups; on many islands of the Kerguelen archipelago, however, the bulk of the diet appears to be algae. *C. minor* can prey on introduced mice *Mus musculus*.

Other Special Features of the Biology

Winter pairings occur at Îles Crozet, in king penguin colonies. Such pairings enable birds to defend high quality feeding territories. Bonds are disrupted in spring, when birds reunite with their previous breeding partners at the onset of the new breeding season.

JOËL BRIED

See also **Cormorants; Crozet Islands (Îles Crozet); Heard Island and McDonald Islands; Kerguelen Islands (Îles Kerguelen); King Penguin; Penguins: Overview; Prince Edward Islands; South Georgia; South Orkney Islands; Southern Elephant Seal**

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SHIRASE, NOBU

Nobu Shirase was born on June 13, 1861, in the small fishing port of Konoura in Akita Prefecture in northeast Japan. As the eldest son of a Buddhist priest, Shirase was expected to follow his father into the priesthood. However, even as a young boy he showed an adventurous spirit, and his interest was caught by the story of the expedition under Sir John Franklin to navigate the Northwest Passage. After months of pestering, his teacher gave him five precepts for an aspiring polar explorer: no alcohol, no tobacco, no tea, no hot drinks of any kind, and never warm yourself at a fire, even in the depths of winter. He also suggested that the army might provide useful mental and physical preparation.

In 1879 Shirase was sent to a Buddhist seminary in Tokyo, but he absconded to join the newly modernised Japanese Army. Posted to Sendai in northern Japan, he had transferred to the Reserves in order to mount a private expedition to the sub-Arctic Kuril Islands when he learnt that Lieutenant Gunji of the Imperial Navy was about to establish a colony there. He persuaded Gunji to take him on despite his army connections and spent from 1893 to 1895 in the northern Kurils. Many of the would-be colonists died, and on his return Shirase wrote a book that was highly critical of the expedition's leader, starting a rift that later almost brought an end to his own Antarctic ambitions.

In the Russo-Japanese War of 1904–1905, Shirase was a reserve second lieutenant in the Medical Corps. He participated in a number of battles, was wounded, decorated, and put in charge of transporting his division back to Japan at the end of hostilities.

By 1909 he was planning an expedition to the North Pole, but on learning of Frederick Cook's and then Robert E. Peary's claims to have attained that point, he, like Roald Amundsen in Norway, turned his attention to Antarctica. In 1910 his sincerity and determination secured the backing of two great men of the Meiji period, General Maresuke Nogi and Count Shigenobu Okuma, and the Antarctic expedition captured the imagination of the Japanese public, eager to show that anything the West could do, Japan could do too. The expedition was funded entirely by private donations and through a public subscription campaign organised by the popular press.

Shirase fought off attempts to postpone the expedition for a year, and when the first attempt to land in Antarctica failed he opted to remain in Sydney with his men to ensure that they would be given another chance. Their successful second effort in the far south vindicated his decisions. They landed on the Ross Ice Shelf, explored, and all returned alive and well to a hero's welcome.

Although the 1910–1912 Japanese Antarctic expedition itself was Shirase's major achievement, he was an honourable man, ensuring by years of poverty and hard work that the expedition's remaining debts were paid by 1935. Two monuments to the expedition were erected in his lifetime, but in the confused and hungry period at the end of WWII, he died in obscurity, aged 85, on September 4, 1946.

HILARY SHIBATA

See also **Amundsen, Roald; David, T. W. Edgeworth; Japanese Antarctic Expedition (1910–1912); Norwegian *(Fram)* Expedition (1910–1912); Ross Ice Shelf**

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SIPLE, PAUL

Polar explorer and geographer Paul Allman Siple (born December 18, 1908, in Montpelier, Ohio) capped a long career in Antarctica, to which he made six expeditions, by leading the first group of eighteen men, and a malemute-husky named Bravo, to live at the South Pole in 1957–1958.

Siple first went to Antarctica in 1928, when he was only 19 years old, as a member of Richard E. Byrd's first Antarctic expedition. Siple was chosen from among 60,000 Boy Scouts of America who applied for the position, and although he was the youngest man on the expedition, he earned the respect of Byrd and his fellow expedition members through his dedication and hard work. His duties included caring for the team's huskies and collecting and mounting seal and penguin specimens.

Upon his return to the United States, Siple earned his BS in biology from Allegheny College in 1932, and later earned a doctorate in geography from Clark University. In 1933, he returned to Antarctica as chief biologist with the Byrd's second Antarctic expedition. He also directed the construction of Advance Base 100 miles south of Little America (at which Byrd spent 5 months alone) and led a group that explored Marie Byrd Land, east of Little America.

On the US Antarctic Service Expedition of 1939–1941, Siple was the leader of West Base, known as Little America III, located at the Bay of Whales on the Ross Ice Shelf, and was the navigator on exploration flights over the continent. He also devised, with Charles Passel, the windchill index to measure the cooling effects of moving air on the human body.

During World War II, Siple served in the US Army Quartermaster Corps and performed research on clothing for polar and tropical climates. He was the Army's senior observer on Operation Highjump (also known as the US Navy Developments Project) of 1946–1947, and returned to Antarctica two more times, in 1955–1956 with Operation Deep Freeze, and in 1957–1958 for the International Geophysical Year (IGY).

At Byrd's personal insistence, Siple served as scientific leader of the US station at the South Pole during the IGY. Although the divided command structure, with a scientific leader and a military leader, could have been problematic, Siple's long polar experience and his large capacity for labor, despite being the oldest member of the team, helped ensure a harmonious year. Lieutenant John Tuck, the base's military leader, wrote in the foreword to *90° South:* "It was leadership by leading, not pushing." The group not only proved that it was possible to survive a winter at the South Pole but also investigated the area's weather and ionosphere as well as the snow layers beneath the base.

When Siple died in his office in Arlington, Virginia, on November 25, 1968, he had spent more cumulative time in Antarctica than anyone before. "Once you've been here," he told a reporter in Antarctica, "there's something a little special about you—everyone feels it, and so do you."

Jeff Rubin

See also **Byrd, Richard E.; International Geophysical Year; Ross Ice Shelf; South Pole; United States (Byrd) Antarctic Expedition (1928–1930); United States (Byrd) Antarctic Expedition (1933–1935); United States Antarctic Service Expedition (1939–1941); United States Navy Developments Projects (1946–1948)**

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SKUAS: OVERVIEW

The skuas are seabirds in the family Stercorariidae, closely related to the gulls. The smaller skuas are called jaegers in North America. In the Southern Hemisphere, there are three species: the South Polar skua *Catharacta maccormicki,* the Chilean skua *C. chilensis,* and the brown skua "group" comprising the Tristan skua *C. antarctica hamiltoni,* the Falkland skua *C. antarctica antarctica,* and the Subantarctic or brown skua *C. antarctica lonnbergi*. In the Northern Hemisphere, there are four species, the great skua *C. skua,* and three smaller *Stercorarius* species, the Arctic skua or parasitic jaeger, *S. parasiticus,* the pomarine skua or jaeger *S. pomarinus,* and the long-tailed skua or jaeger *S. longicaudus,* with the two subspecies *S.l. longicaudus* and *S.l. pallescens*. There are three species of jaegers, which are quite distinct. No such certainty exists for the great skuas, which are all rather similar. Hybridisation between Subantarctic and South Polar skuas occurs along the Antarctic Peninsula and nearby islands, and at Dumont d'Urville in East Antarctica, between Chilean and Falkland skuas in Patagonia, and between Chilean and South Polar skua on the South Shetland Islands.

Skuas are in general medium-sized to large birds, typically with brown or grey plumage. They have conspicuous white patches at the base of their flight feathers, wedge-shaped tails, a mostly black, heavy bill with a hooked tip, and webbed feet with sharp claws. In appearance, skuas look like immature gulls, although heavier and more robust. Their flight is usually heavy, with much flapping and relatively little gliding. In the past, two groups of skuas were recognised: the large skuas—big, heavy, brown birds, with several species in the Southern Hemisphere and one on North Atlantic islands, and the small skuas or jaegers—smaller, lighter, often with patterned and barred plumage and, when breeding, long tail feathers. The skuas and jaegers show variation in plumage in three circumstances: adults exhibit breeding and nonbreeding plumages, young birds take several years to achieve adult plumage, and polymorphism—there are dark and light adult morphs of the same species. It is relatively difficult to identify the large skuas of the Southern Hemisphere. They are all closely related and very variable, and they are all oceanic between the time they leave the natal colony as juveniles and their return as adult birds to their breeding grounds. The taxonomy of the brown skua "group" is uncertain, and different authorities follow different taxonomies.

The South Polar skua is smaller than other southern skuas, and has a smaller head, a flatter crown, shorter legs, and a shorter (black) bill. The body mass ranges between 0.7–1.7 kg. With their narrower and relatively longer wings, these birds appear less heavy in flight than many other species. They are polymorphic and highly variable, with light (cream), brownish, or blackish-brown plumage. The pale (and intermediate) morphs have a pale head and underparts, a greyish creamy-brown or buffy-cream (to medium or dark cold brown) colour, but the wings and the rest of the upperparts are very dark. The nape is streaked with light colour and buff forming a large patch with golden hackles in summer. The dark morphs are entirely sooty blackish-brown with a darker face and upperparts. In the breeding season, they also have golden hackles on the nape. Juveniles of all morphs look like intermediate morphs: they are greyish with dusky-brown upperparts, a black-tipped grey bill and greyish legs. They have no neck patch.

Tristan skuas (body mass 1.2–1.8 kg) are generally brownish, gull-like skuas with bold white flashes on the primaries visible in flight. Their appearance seems to be intermediate between brown and Falkland skuas. They are smaller than brown skuas but have relatively longer legs and a longer bill. The adults have a uniform dark brown head and neck, intermediate between Falkland and brown skuas. Juveniles, which are also generally intermediate between brown and Falkland skuas, are dark brown all over with a slightly darker hood. The underparts are a warmer reddish-brown, and the upperwing coverts are buffy-rufous in colour.

The Falkland skua is similar to brown and Tristan skuas but smaller and slighter with proportionally longer legs and stronger bill in relation to a more rounded head shape. This species looks intermediate between the great skua and the brown skua but closer to the former in shape and general plumage. The adults are quite variable in colouring but often have a contrasting darker cap and numerous streaks on the neck and breast. The mantle and upperwing-coverts have nearly no pale streaks, but the flanks and breast are streaked. Juveniles are principally dark brown, with a darker hood.

The brown skua is larger and heavier than all other forms, with proportionally shorter legs, a smaller head, and a more powerful bill. The neck looks very thick. The head of adults is generally dark, but the degree of pigmentation varies, and sometimes the crown is dusky and there are yellow streaks on the nape of the neck. The plumage is variable; the base colour is brownish, ranging from a deep chocolate brown to fairly light brown. The underparts are generally lighter than the upperparts. One important feature is pale streaks on the mantle and upperwing-coverts. Juveniles are uniformly dark chocolate brown. The underparts are buffish-cinnamon. Brown skuas fly fast, with fairly rapid powerful wingbeats, and they can be extremely agile.

Chilean skuas, compared to the brown skua group, are smaller and slighter, with a proportionally less powerful bill, narrower wings, and slimmer tail, body and neck. Most of the adults are characterised by a blackish-brown cap contrasting with the paler neck and body. They have light cinnamon underparts (including the underwing-coverts). A blue bill with a dark tip is an additional feature that contrasts with other skua species. The neck and mantle are streaked with cinnamon. Juveniles are generally much more uniform in colouring, with more intensive cinnamon colouration of the underparts.

The *Stercorarius* skuas or jaegers are generally a small or medium-sized species, different from the much larger, mostly brown, *Catharacta* species. They are lightly built skuas, and most are typically fast flyers on long wings. The flight is relaxed and elegant with powerful wingbeats. From afar, they appear dark with extensive grey-brown patches. In adults, the middle tail feathers are prolonged in breeding plumage. In the Antarctic, birds with winter plumage are seen, and species determination requires very careful observation of the diagnostic species-specific differences.

The pomarine skua or jaeger is the largest *Stercorarius,* heavier, longer winged, and with more direct flight than other species. There are pale and dark adult morphs. The pale patch on the primaries is similar to, or bigger than, that in Arctic skuas but narrower than that in *Catharacta* species. In the Antarctic summer, the period in which they have sometimes been observed in the far south, the characteristic long and broad oval-ended tail streamers are absent. The bill is yellowish/greyish-brown with a black tip. The light morph looks almost dark dorsally and has a dusky breast band on whitish underparts. The dark phase has whitish wing patches but is otherwise browner than during breeding plumage. The juveniles and immatures, mostly barred on the underparts, are more difficult to distinguish from those of the other two species.

The Arctic skua or parasitic jaeger, is a medium-sized, dark-looking seabird with long narrow wings that are completely dark, and pale patches at the wingtips. Its elegant flight shows falcon-like wing beats. There are two phases, a dark and a predominant pale one. In the southern summer, the characteristic long, narrow tapering tail-streamers are almost entirely absent, but these are partially regrown by February/March. Arctic skuas have a blackish grey-brown bill. Light morphs have a pale rump, whereas dark morphs are entirely sooty-brown except for the whitish wing patches. In the southern summer, they look less uniformly coloured on the body and appear variably light barred.

The long-tailed skua or jaeger is the smallest *Stercorarius* species and, especially in flight, is slighter, more slender-bodied, and narrower-winged than other species. The flight is ternlike and appears relaxed. During the breeding season, the birds have remarkably long tail feathers. The adults are variable in coloration and, unlike other *Stercorarius,* they have no pale primary patches under the wings. Light coloration is restricted to whitish shafts of the outermost primaries. In the southern summer, the long tail streamers are almost lacking, but they begin growing at the end of the summer. During this time, the blackish cap is less solid, and they have a dusky breast band and barred flanks.

The *Stercorarius* skuas all breed in the Arctic and migrate to the Southern Ocean after breeding. Arctic skuas are circumpolar breeders on the Arctic tundra, coastal areas and islands, sometimes in small colonies. In March to May and August to November, they migrate to the Southern Hemisphere. In the southern summer, some individuals reach Antarctic waters as far as 65° S.

Long-tailed skuas are circumpolar breeders in the Arctic tundra and coastal mountains. They disperse and are found over all the World's oceans in March to May and August to November. In the southern summer, they reach the overwintering oceanic areas around southern Africa, near the Patagonian coast, and in the South Pacific Ocean. During this period, individuals have been observed in Antarctic waters (reaching 70° S) more often than other *Stercorarius* species.

Pomarine skuas have an almost circumpolar distribution and breed in Arctic tundra, shore areas, and coastal mountains. Outside the breeding season, they migrate over all the World's oceans in March to May and August to November to reach the wintering areas near northwest South America, the western Atlantic Ocean, and west Africa. The wintering areas are more northerly than those of the two other species, as only a few have ever been observed in Antarctica.

All large skua (genus *Catharacta*), with the exception of the great skua in the North Atlantic Ocean, have their breeding range in the Southern Hemisphere. The South Polar skua (5000–8000 estimated breeding pairs) breeds on the Antarctic coast and on a few islands at the northern tip of the Antarctic Peninsula. Falkland skuas breed on the Falkland Islands (5000–9000 breeding pairs) and the Patagonian coast. Brown skuas have a circum-Antarctic distribution while breeding, mainly on sub-Antarctic islands and on islands in the Antarctic Peninsula region. This distribution is partly sympatric with that of the South Polar skua. Tristan skuas breed only on Tristan da Cunha and Gough Island (2500 breeding pairs). The breeding range of Chilean skuas is in southern Chile and southern Argentina (several thousand breeding pairs), but the number of birds observed in the Antarctic Peninsula region is presently increasing.

Skuas use marine habitats most of the year, especially when not breeding. Long-tailed skuas are more oceanic, especially in winter, whereas great skuas use areas over the continental shelf. Arctic skuas migrate and overwinter not far from coasts. Chilean skuas winter in the channels, straits and fjords of southern Chile and Argentina. The wintering areas for different species range from sub-Antarctic areas for long-tailed and brown skuas to tropical oceans for pomarine skuas. Only some of the most northerly distributed subspecies of the brown skua group on sub-Antarctic islands remain at their breeding sites over winter, feeding on winter-breeding birds and visiting seabirds.

Antarctic skuas breed during the summer months. South Polar skuas arrive at their breeding colonies in late October to mid-December, depending on latitude. Most skuas show high site fidelity and are monogamous. An exception is that some female brown skuas breed with two males, forming breeding trios. Breeding pairs renew the pair bond after returning to the territory that they used in former years. Few birds lose their partner over winter, since adult survival is very high. After courtship, one or more nest scrapes are formed and the eggs are laid in one of them in December or January. The eggs are mottled, and usually the two are laid 2 days apart, although there is sometimes only one egg. If eggs are lost, they are usually replaced by replacement laying. Breeding skuas are highly territorial and will attack unwelcome intruders (including humans) by flying straight at their heads, claws outstretched. Incubation begins with the first egg, and the chicks hatch asynchronously after 29–30 days. In the South Polar skua, lethal sibling aggression is common and results in brood reduction from two hatchlings to a single chick. The first chick to hatch attacks the second within a day or two of its hatching and either chases it from the nest area or maims it so severely that it dies. Young birds are fully fledged by early February and are capable of flight within 35–40 days of hatching. In relation to other seabirds, the breeding success is relatively high but very variable. It depends not only on variations in the amount of food but also on the weather. Fledged skuas tend to return to the natal area after some years but until then remain in the wintering areas throughout the year. Skuas are long-lived, with a 34-year-old skua known.

Skuas are primarily predatory or kleptoparasitic in their foraging behaviours. When attacked by a skua, other birds will often drop or regurgitate their food that the pursuing skua then seizes and consumes. Tundra-nesting *Stercorarius* skuas feed on small mammals, especially lemmings, but also on small birds including waders, eggs, carrion, insects and sometimes berries. The exact combination of items taken differs among species. *Catharacta* skuas are an opportunistic species, preying mostly on marine invertebrates and fish in winter, and on birds in the breeding season. Brown skuas are the main predators of penguins and other seabirds, mostly during the daytime. However, they will also hunt at night for burrowing nesting petrels because these are inactive in the colonies during the daytime. South Polar skuas mainly eat fish, which are often obtained by robbing other seabird species.

Hans-Ulrich Peter

See also **Antarctic Peninsula; Chilean Skua; Fish: Overview; Insects; Penguins: Overview; Seabirds at Sea; South Polar Skua; South Shetland Islands; Sub-Antarctic Skua**

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SNOW BIOGENIC PROCESSES

The Antarctic ice sheet records present and past biological activity through the presence of biochemical markers and life particles (bacteria, viruses, microalgae) incorporated in the snow. Since biological activity in the snow is believed low, the biomarkers are mainly related to biological activity in the Southern Ocean (SO), whose proxies are transferred to the snow by wet and dry deposition. Antarctic ecosystems show two peculiar features: the role of sea ice in controlling the phytoplankton seasonal pattern and the possible preservation of ancient microbic life in fossil ice and subglacial lakes.

Southern Ocean Relevance

The SO is an important sink for atmospheric CO_2, at least during phytoplankton blooms. Mechanisms governing vertical stability and thermohaline circulation make the SO sensitive to climate change, with consequences for CO_2 regulation. The seasonal sea-ice cover (20 million km^2 in winter) inhibits gaseous ocean/atmosphere exchange, but the growth of sea-ice microbial communities has important implications for carbon, sulphur, and nitrogen cycles. Microphytoplankton, predominantly diatoms, contribute much of the SO primary production, especially in frontal and neritic areas and at the ice edge. However, nanoplankton and picoplankton dominate in some areas and seasons. In the Polar Frontal Zone (PFZ), and in the Marginal Ice Zone (MIZ) in winter, biomass and productivity are low, nutrient concentrations are high, and aqueous CO_2 concentrations exceed atmospheric concentrations. Only zooplankton, mainly krill and large copepods, are abundant and active under the ice and between ice floes. In spring, phytoplankton blooms involve different species assemblages; in the PFZ, diatom *Corethron* spp. and *Fragilariopsis kerguelensis* dominate. Bacterial biomass follows phytoplanktonic development. Grazing by zooplankton (mainly copepods and *Salpa thompsoni*) impacts phytoplankton production. In the MIZ, the seasonal pattern of biological and biogeochemical processes is dominated by changes in sea-ice cover, which influence the ocean-atmosphere fluxes of heat and materials and modify underwater illumination. When ice melts, the superficial low-salinity water prevents vertical mixing, enhancing the nutrient availability and leading to ice-edge phytoplankton blooms. The MIZ might contribute as much as 40% of the SO total photoautotrophic carbon fixation. Large-celled diatoms in open water conditions dominate phytoplankton, whereas small algae, mainly flagellates, prevail under the ice. Phytoplankton biomass concentration exceeds 7 mg Chl *a* per m^3 in the bloom, which comprises large centric diatoms together with *Phaeocystis*. In coastal Weddell Sea areas, *Eucampia balaustium, Trichotoxon reinboldii, Chaetoceros dichaeta,* and *Phaeocystis* spp. are dominant. Grazing pressure (protozoan species such as oligotrich ciliates and dinoflagellates, and smaller zooplankton dominated by copepods) is very high during the phytoplankton bloom.

Iron Hypothesis

The SO is the major high-nutrient, low-chlorophyll (HNLC) oceanic region, where low annual primary production occurs although efficient vertical mixing supplies high-nutrient concentrations. Here, the lack of oligo-elements or micronutrients constitutes a limiting factor for the phytoplankton growth. Fe may play a relevant role in controlling primary productivity in HNLC areas and, subsequently, in atmospheric CO_2 uptake, as shown by seawater iron-enrichment experiments where small amounts of Fe sped up the growth of large-celled diatoms (e.g., Nitzchia). Fe availability in superficial seawater potentially affects the climate by controlling the biogenic emissions (which rule cloud formation) and the greenhouse-gas global balance. In glacial periods, when higher dust atmospheric loads occurred, larger deposition of Fe on the ocean surface could have increased the phytoplankton activity, contributing to lower atmospheric CO_2 concentrations. Fe, dust, methanesulphonic acid (MSA), and CO_2 measurements are currently carried out on ice cores to assess the correlations between mineral supply, paleoproductivity, and greenhouse gases.

Biogeochemical Cycles

Several chemical compounds are measured in ice cores to reconstruct the oceanic biological activity and its relationship with climate.

CH_4 and volatile organic compounds (VOCs) dominate the sea-atmosphere-snow C-cycle. Atmospheric CH_4 mainly arises from microbial breakdown of organic compounds in anaerobic conditions, such as in SO anoxic seawater layers and sediments. A large range of VOCs (hydrocarbons, alcohols, carbonyls, carboxylic acids, fatty acids, and esters) is produced in surface seawater by photochemical mechanisms, phytoplankton activity, and/or microbial breakdown of organic matter, so showing a strong seasonal pattern. The ocean-atmosphere flux is dominated by alkenes and is small compared to terrestrial emissions (<1%). While VOCs are rarely measured in Antarctic ice cores, CH_4 in ice air-bubbles is used in understanding the greenhouse gas–climate correlations, in reconstructing the past wetland extension and in synchronising ice-core time scales.

NH_3 is the dominant gas-phase alkaline compound in the marine atmosphere and is produced in seawater and sediments by degradation of organic nitrogen-containing compounds. Penguin colonies constitute a major source of NH_3 in coastal regions, via microbial breakdown of urea and uric acid in animal waste. Atmospheric NH_3 reacts with nitric and sulphuric acids to give ammonium salts, which are scavenged to the ice sheet by wet deposition. High-resolution ice-core NH_4^+ stratigraphies are used in reconstructing past biogenic activity in oceans and wetlands around Antarctica.

Biogenic dimethylsulphide (DMS) is the main volatile sulphur compound in oceanic remote regions. Atmospheric DMS is oxidised to H_2SO_4 and MSA, which act as Cloud Condensation Nuclei (CCN), affecting cloud albedo, the hydrological cycle and, consequently, the climate. Large-scale climate changes, in turn, influence the phytoplankton productivity, completing a feedback loop. However, the spatial correlation between DMS and phytoplankton concentrations is not straightforward because intracellular concentration of its metabolic precursor, dimethylsulphoniopropionate (DMSP), in different phytoplankton species varies over a range of five orders of magnitude. Very high DMS and DMSP concentrations have been measured at high latitudes, especially during phytoplankton blooms of coccolithofore *Emiliania huxleyi* and prymnesiophyte *Phaeocystis pouchetii*. Diatoms are less important DMS producers. DMSP lyase enzymes, present in some phytoplankton species, increase the DMS emissions. Zooplankton plays a role by grazing, or avoiding, DMSP-rich cells. Bacteria can metabolise DMSP through different pathways, decreasing DMS production. Viral infections can cause a total release of intracellular DMSP in species such as *Emiliania huxleyi* and *Phaeocystis* sp. Several physical-chemical parameters (solar radiation, vertical mixing, temperature, sea-ice cover) affect the sea-atmospheric DMS exchanges (10–50 Tg S yr^{-1}). Atmospheric DMS oxidation pathways to form non-sea-salt sulphate ($nssSO_4^{2-}$) and MSA are complex, and relative yields are influenced by temperature and latitude.

MSA and $nssSO_4^{2-}$ ice-core stratigraphies potentially allow us to reconstruct past phytoplanktonic activity. Unfortunately MSA, univocally originated from DMS, is affected by post-depositional processes, which make difficult the interpretation of its temporal changes in low accumulation-rate sites. Where preserved, MSA is correlated with sea ice cover, southern atmospheric circulation, and phytoplanktonic activity. During the sea ice buildup, impurities and nutrients are excluded from the ice latex and incorporated in the pack interstitial spaces (brine pockets). In winter, different algae assemblages survive in brine pockets protecting itself against the high salinity and the low temperatures by producing intracellular DMSP, which is an osmolyte and a cryoprotectant. DMSP is excreted out from the cells when they experience a much lower salinity due to the sea ice melting in spring. In addition, the low-salinity layer stratification concentrates the nutrients coming from sea-ice melting and, together with the increasing solar radiation, primes the phytoplanktonic blooms. Ice-core measurements revealed higher MSA and $nssSO_4^{2-}$ concentrations in glacial periods, suggesting higher phytoplankton productivity occurred; however, recent measurements at Dome C revealed that $nssSO_4^{2-}$ fluxes were quite constant at least in the last 45 kyr.

Subglacial Lakes

Subglacial lakes constitute a peculiar Antarctic feature. The unique extreme characteristics of Lake Vostok (–3.2°C, 400-bar pressure, absence of light, possible absence of oxygen, unknown conditions of salinity, nutrient concentration, and energy sources) evolved for millions of years in almost total isolation from the biosphere. The presence of autochthonous microorganism and the preservation of ancient life species appears to be plausible, as well as the slow (about 1-million-year) sinking of living species from the outer atmosphere through the ice column. Preliminary studies show the presence of 10^3–10^4 bacterial cells/cm^3 of Actinomyces in glacial ice under Vostok and estimate that the Antarctic subglacial lakes and ice sheet contain 1.2×10^{25} – 8.8×10^{25} prokaryotic cells, corresponding to a total bacterial carbon content of 2.8×10^{-3} Pg C. This value approaches that reported for Earth's combined lakes and rivers, making the icy systems of Antarctic a significant organic carbon reservoir. Taxonomic analysis by molecular techniques showed that the largest number of the sequences belong to Proteobacteria α and β (*Acidovorax* and *Comamonas*). Subglacial lake studies have relevance in understanding the adaptation mechanisms to extreme life environments and in refining noncontaining methods for extraterrestrial sub-ice explorations (Europe, Jupiter's satellite).

ROBERTO UDISTI

See also **Algae; Atmospheric Gas Concentrations from Air Bubbles; Bioindicators; Climate Change; Climate Change Biology; Earth System, Antarctica as Part of; Ice–Atmosphere Interaction and Near-Surface Processes; Ice Chemistry; Ice Core Analysis and Dating Techniques; Marginal Ice Zone; Paleoclimatology; Phytoplankton; Polar Front; Precipitation; Snow Chemistry; Snow Post-Depositional Processes; Subglacial lakes; Zooplankton and Krill**

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SNOW CHEMISTRY

Accumulating snow strata faithfully record the local atmospheric aerosol composition. On the other hand, gases are entrapped in ice bubbles formed far below the snow surface (up to 1–2 millennia later) when firn transforms into ice. Most atmospheric particulate impurities are incorporated in the snowflakes at cloud level. However, due to the penetration of air into surface snow (an effect called wind pumping), the filtering of atmospheric particles by porous snow is suspected to be responsible for an additional "dry" contribution to impurity deposition, particularly in central regions where accumulation rates are extremely low (<5 g/cm^2/yr). The deposition mechanism of HCHO (formaldehyde), acid gases like, HCl, HNO_3, methanesulfonic acid (MSA), and carboxylic acids is more complex. The incorporation of these compounds in snow is reversible, and in central regions, due to low accumulation rates, they partially return to the free atmosphere during firnification.

Analytical methods used in glaciochemistry (the study of polar snow chemistry) are derived from rain analysis, with many additional precautions required by the extreme cleanliness of polar precipitation. For soluble ionic species, ion chromatography is commonly used. Insoluble materials are generally analysed by microparticle counting, Inductively Coupled Plasma Mass Spectrometry (ICP-MS) or Atomic Absorption.

Antarctica is surrounded by large ocean surfaces. It is therefore not surprising that the chemical composition of snow is typical of a marine region, with an important contribution of sea salt and secondary aerosol derived from gaseous sulphur species emitted by marine biogenic activity. Coastal regions are strongly influenced by the marine boundary layer, with a high concentration of sea salt in the air and in the snow, whereas the high central Antarctic plateau is more influenced by the middle free troposphere where the impurity content is extremely weak. Sea salt concentration in Antarctic snow decreases rapidly with elevation. Its composition may be modified (in particular the Cl/Na ratio) by post-deposition processes. The amount of continental dust is extremely weak everywhere on this continent (less than 10% of total mass deposition).

Regional volcanic eruptions may form ash deposits at the surface of the ice sheet, but such events are not frequent. On the other hand, cataclysmic volcanic eruptions located at midsouthern or tropical latitudes inject gaseous sulphur compounds into the stratosphere. Such eruptions are recorded in Antarctic snow by sulphuric acid spikes of 1–2 year duration. The background level of sulphate in the snow is linked to marine biogenic activity (dimethylsulfide, or DMS, emissions by zooplankton), as at other latitudes around the world. Its typical concentration in the snow is 1–3 μ Equivalent/l. The second important sulphur species is MSA. It is directly related to oceanic DMS emissions, but the information recorded in Antarctic snow is frequently plagued by post-deposition effects.

There is still a debate concerning the origin of nitric acid, the major nitrogen species found in Antarctic snow. Photochemical reactions in surface snow, detected only recently, may change initial nitrate concentrations, but the most important perturbation in central regions is caused by the firnification process. Organic compounds, in particular carboxylic acids, are interesting atmospheric chemistry markers, but their study in Antarctic snow is still in its infancy.

Concentrations of the various chemical compounds vary as a function of depth in relation to seasons and global and regional climate. Their study along ice cores provides information on the environmental conditions of the past.

ROBERT DELMAS

See also **Atmospheric Gas Concentrations from Air Bubbles; Firn Compaction; Ice–Atmosphere Interaction and Near-Surface Processes; Ice Chemistry; Ice Core Analysis and Dating Techniques; Isotopes in Ice; Pollution Level Detection from Antarctic Snow and Ice; Snow Biogenic Processes; Snow Post-Depositional Processes; Volcanic Events**

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SNOW PETREL

Snow petrels (*Pagodroma nivea,* the smallest member of the petrel family Fulmarinae) nest in coastal and inland regions of Antarctica (up to 440 km inland from the coast) including the Antarctic Peninsula but also in South Georgia, islands of the Scotia Arc, Bouvetøya, Balleny and Scott Islands. This species is highly associated with snow and sea ice in its habitat use and in its name, for *pagos* is the Greek for ice, and *niveus* is the Latin for snowy.

Snow petrels are medium-sized, all-white petrels with contrasting black eye, and a bill that is blue-black. The legs and feet are also blue-black. Compared with most petrels, the flight involves little gliding, and the birds fly among the pack ice and icebergs with shallow wing beats. Their white plumage, specialised for life in the high-polar habitats and buoyant flight make the snow petrel the ecological counterpart of the ivory gull *Pagophila eburnean* in the Arctic. A peculiarity of snow petrels is the great body size range among individuals and the great sexual dimorphism. The largest individuals are c. 50% heavier than the smallest. Although snow petrels have been divided into two subspecies based on body size differences, there is no consensus on their validity since some colonies have varying proportions of small and large birds. It has been suggested that the larger form evolved around the Balleny Islands, and a smaller form around the Scotia Sea during the Pleistocene, and that in today’s climate the two forms have spread from their respective refugia and hybridize at several localities. Today, several selective forces, such as predation by South Polar skuas *Catharacta maccormicki,* shape the proportions of small and large individuals within populations.

The size of the world population is poorly known. Although the at-sea estimates include around 2 million individuals in the Ross Sea and 1.7 million in Prydz Bay, counts at known breeding localities total only 63,000 pairs. This marked mismatch suggests that many breeding localities remain to be discovered on ice-free coastal areas but probably also on inland nunataks at substantial distances from the Antarctic coast.

Because of the relatively small size of snow petrels, which prevents their tracking with satellite tags, and makes it difficult to observe the behavior of individuals in their natural habitat (pack ice), the at-sea feeding behavior is poorly known. Snow petrels usually feed in the vicinity of the ice, especially where ice cover is 10%–50%, finding food in the leads between the pack ice and around icebergs. Most individuals were observed feeding by dipping, surface-seizing, and surface diving. They take mainly fish, but also crustaceans and cephalopods, with the proportions varying with season and location.

Snow petrels breed during the short Antarctic summer, usually in colonies of tens to hundreds of pairs. The largest known colony has c. 20,000 pairs. Snow petrels return to their traditional nesting sites in late October or early November. Nests are in crevices on cliffs or steep slopes and are sparsely lined with small pebbles, bones, and feathers. Competition to obtain a nest not obstructed by ice is high, and nest entrances may be surrounded by solidified oil (wax spat against intruders to protect the nest) accumulated over centuries or longer. Once at the breeding sites, laying occurs during the first 2 weeks of December, after a prelaying exodus at sea of nearly 20 days, and is highly synchronized and similar at most sites. Incubation is approximately 44 days. Male and female share the incubation duties and alternatively incubate the egg and forage at sea in approximately 8-day shifts. Once hatched, the chick is brooded by the parents for 4–7 days and then left unattended until fledging. During the chick-rearing period parents make foraging trips of 40–70 hours in average. The chick period lasts approximately 47 days, and most chicks leave the colonies by late February or early March. As for the other fulmarine petrels, snow petrel chicks grow at a considerable rate, about twice as fast as predicted allometrically.

Adults breed in only 52% of seasons during their reproductive lifetime, and half of the eggs laid fledge a chick on average. The percentage of fledged chicks increases when air temperatures in spring are higher than average, and the proportion of eggs hatched is higher when females are in good physical body condition. Because of the high competition to obtain an unfrozen nest site, nest and mate fidelity are very high (c. 90%). After fledging, individuals stay at sea for several years and the average age at first breeding approaches 9–10 years. The annual adult survivorship is high, (95% for males, 94% for females). After winters with greater sea ice extent and cover, the number of breeding pairs and the proportion of breeding adults in a colony may increase.

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See also **Balleny Islands; Bouvetøya; Ross Sea; Seabird Conservation; Seabird Populations and Trends; South Georgia; South Polar Skua**

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SNOW POST-DEPOSITIONAL PROCESSES

Firn is the porous and permeable layer of compact snow encountered on top of polar ice sheets. It represents the interface between the atmosphere and the impermeable ice strata where atmospheric gases are permanently encapsulated and thus plays an important role in the formation of polar environmental archives. Its thickness is typically 50–120 m, depending on local temperature conditions and the snow accumulation rate.

Recent measurements in the high Arctic have revealed that photochemical processes may occur within surface snow in summer, leading to high levels of NOx (NO + NO_2) and formaldehyde (HCHO) in the interstitial air of snow. These reactions, probably also present in Antarctic snow, may have a significant impact on the tropospheric ozone budget of these regions and could change the original HNO_3 or HCHO content of deposited snow. Wind pumping, another phenomenon affecting the upper snow layers, is responsible for dry deposition of atmospheric impurities by air filtering and for the mixing of the upper firn strata (down to 10–15 m) where gas convection is active and exchanges with the free atmosphere are still observed.

Marked chemical changes are observed in the snow layers during firnification, the physical process that turns snow into ice. The transformation can take several decades to centuries. It involves the internal distillation of water vapour and sintering of ice crystals.

After snow deposition and during firnification, gases entrapped in snowflakes at cloud level or eventually formed *in situ* by chemical reactions can be released into the gaseous interstitial phase of firn (initially containing only atmospheric air) and modify its composition. If the release occurs within the convective zone (0–10 m), the final effect is negligible since released gases escape readily to the free atmosphere. However if it occurs deeper, the perturbation can be significant. This process could explain the difficulty of obtaining reliable CO_2 concentration measurements from Greenland ice cores for glacial climatic periods: at that time, carbonate dust reaction with snow acidity produced extra amounts of CO_2, disturbing markedly the air bubble CO_2 content.

The region of open pore space where molecular diffusion and gravitation are dominant extends down to a depth referred to as the close-off depth. Gravitational settling enriches the heavier molecules at the bottom of the stagnant air column whereas diffusion triggers a separation of the molecules according to their diffusivity properties. Therefore the interpretation of gas records from ice cores requires the use of a reliable model quantifying all these physical and chemical processes that affect gas composition (and isotope ratios of several trace gases) along the firn strata.

At extremely low accumulation sites (a<5 g cm^{-2} a^{-1}), the concentrations of Cl and NO_3 ions and methanesulfonate (an indicator of marine biogenic activity in the sub-Antarctic ocean) show a steep decrease in the first 5 m of firn, as opposed to dust and salt particle concentrations that remain far more stable. Post depositional processes affecting the three gases HCl, HNO_3, and methanesulfonic acid cast doubt on the reliability of their records obtained from central Antarctic ice cores as indicators of past atmospheric contents. For the case of Cl (a species associated with sea salt aerosol), this observation indicates that part of this ion is in the form of hydrochloric acid (HCl) and that this gas is released from the ice matrix after deposition. This has an indirect negative consequence regarding the use of the cosmogenic radionuclide ^{36}Cl (half-life 301 Kyr) as a dating tool for deep ice cores.

Robert Delmas

See also **Antarctic Ice Sheet: Definitions and Description; Atmospheric Gas Concentrations from Air Bubbles; CryoSat; Firn Compaction; Ice–Atmosphere Interaction and Near-Surface Processes; Ice Chemistry; Ice Core Analysis and Dating Techniques; Ice Sheet Mass Balance; ICESat; Isotopes in Ice; Mega-Dunes; Pollution Level Detection from Antarctic Snow and Ice; Snow Biogenic Processes; Snow Chemistry; Surface Energy Balance; Surface Features; Volcanic Events**

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SOILS

Antarctic soils lie at the extreme end of the global soil spectrum. They occur in an environment where the essential factors for soil formation (available moisture, temperature or climate regime, and biological activity) are at minimal levels; consequently Antarctic soils express the interaction of some of the most extreme terrestrial conditions found on earth. In global terms, Antarctic soils are classed as Cryosols, or soils subject to continuing disturbance by freeze/thaw action. They are also referred to as Cold Desert soils, or Polar Desert soils in the Antarctic Peninsula region where conditions are a little warmer. These terms emphasise that soil formation takes place under the coldest and driest conditions on Earth. A distinguishing feature of Antarctic Cold Desert soils is the absence of a significant organic component, which elsewhere in the world provides the mechanism for recycling nutrients and assisting the chemical decomposition of mineral materials. The two main processes operating in Antarctic soils are salinization, or the accumulation of salts and oxidation, and the slow release of iron oxides.

The severity of Antarctic environmental conditions for soil formation, as well as for the existence and survival of the few organisms that are found, is illustrated by soil climatic data from a station near Lake Vanda (altitude 200 m) in the Dry Valleys. The mean annual air temperature at the recording site is approximately –23°C while surface soil temperatures range from +15°C for a few days in summer to –45°C in winter. In summer, the surface soil temperature fluctuates by up to 15°C daily, with freeze and thaw cycles occurring from mid-November to mid-February, after which the soil remains frozen. During winter, soil temperatures may fluctuate by 35°C with changing weather systems. Below the soil surface, temperatures are much cooler with the thaw depth reaching 35 cm on just a few days. Elsewhere the climate differs markedly from this site, with a warmer climate and soil temperatures in the coastal regions and much colder temperatures in inland valleys and at higher altitudes. The main source of water for soil processes is moisture derived from periodic summer snowfalls. However, much of the snow that falls sublimates, and the small amounts that may enter the soil are usually lost through evaporation within a few days. Soil moisture, an essential requirement for life and geochemical processes, is normally present at low levels and in some Dry Valley soils is less than 1% gravimetric (by weight).

The area of exposed land on the Antarctic continent has been estimated to cover only about 0.3% or approximately 46,000 sq km, the majority of this occurring in the Transantarctic Mountains and Dry Valleys. Most of this land is covered with glacial till, the principle material from which the soils are formed. Antarctic soils have a number of distinctive characteristics. The active layer is that part of the soil that is subject to annual freezing and thawing. In coastal and northern regions, the active layer may exceed 1 m, but the depth decreases with increasing altitude and is less than 10 cm in inland mountain areas. Permafrost, or permanently frozen soil, underlies the active layer and is commonly icy and very hard in the warmer and moister coastal regions but is loose or dry-frozen inland, where colder and more arid soil conditions prevail. The surface of the soil is typically covered with a stone pavement that in the initial stages of soil formation may comprise unstained boulder material left after glacial retreat. Below the ground surface, younger soils are typically loose, unoxidised, olive grey coloured sandy gravel, overlying ice-cemented permafrost. On the oldest land surfaces, the surface boulders are reduced by weathering (abrasion and disaggregation) to form a stone or desert pavement of flattish, oxidised and sometimes polished or pitted pebbles. As the land surface and soil age increase, the subsurface soil colour changes from olive grey to yellowish brown or red, the increasing redness resulting from cumulative oxidation with increasing time. The depth to which oxidation occurs in the soil also increases with time and increasing surface age. Older soils are usually a little more cohesive, contain rocks that are partly decomposed or disaggregated, are dry frozen, and have accumulations of soluble salts. The salts may occur in a distinct layer, 10–15 cm below the soil surface, or as scattered precipitations. They are dominantly chlorides, nitrates, and sulphates of sodium, potassium, calcium, and magnesium. Some of the salts are released through rock weathering but most are derived from the atmosphere, having been transported via the global atmospheric circulation system. Nitrate salts are common in the most arid inland regions, and chlorides and sulphates in the coastal regions, reflecting differing atmospheric pathways. The salts remain in the soil because the climate is arid with evaporation potential exceeding precipitation, and the amount of salt present increases along with soil age.

Biological activity in Antarctic soils is at minimal or very low levels; consequently accumulations of organic matter are scarce. In the Antarctic Peninsula region, small peaty patches are associated with plant occurrences. Elsewhere, the main organic accumulations are pockets of algal matter around ponds, patches of moss, and the more extensive guano deposits at penguin rookeries. Biological legacies are also important sources of carbon.

The clear development pathway of the soil properties with time, allows Antarctic soils to be used as a tool for estimating land surface ages and constructing the glacial history of Antarctica. Correlation of some soils with deposits of 15 my volcanic ash indicates that in places, the soils and land surfaces date from the Miocene period. The preservation of these ancient soils and associated surface features indicate that Antarctic landscapes are very stable and that the soil weathering processes operate extremely slowly.

Because soil development is very slow and there is no vegetative cover or soil structure, Antarctic Cold Desert soils are very fragile. Disturbances and contaminations from most forms of human activities range from very long lasting to permanent. The soils are an important component of the Antarctic terrestrial ecosystem and require careful management.

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See also **Algae; Antarctic Peninsula; Climate; Dry Valleys; Mosses; Polar Desert; Precipitation; Temperature**

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SOLAR WIND

The solar wind is a supersonically expanding extension of the atmosphere of the Sun, extending out past the planets to form a cavity in the interstellar medium (the Heliosphere). The solar wind originates in the hot corona of the Sun, where temperatures are in the million-degree range. Consequently the material of the solar wind is highly ionised, and so as it expands into space it carries the solar magnetic field with it. The solar wind is thus the agent which carries disturbances in the solar atmosphere out to the Earth and beyond, becoming the driving term for geomagnetic storms and other "space weather" phenomenae.

The first suggestions of a medium carrying magnetic disturbances from the Sun to the Earth were made following the great solar storm of 1859, and between 1888 and 1931 numerous proposals explaining geomagnetic storms in terms of the impact of solar particles on the Earth's magnetic field were put forward. The concept of a continuous, high-speed wind dates from the 1950s, when Biermann suggested that a high-speed electrically neutral outflow of ions and electrons would explain the appearance of comet tails. In 1958 Parker showed that high temperatures in the solar corona would give rise to a continuous supersonic outflow: the existence of this "solar wind" was confirmed in 1962 by measurements from the *Mariner 2* spacecraft.

At periods of minimum solar activity the solar wind is highly bimodal, comprising distinct fast (600–800 km/s) and slow (300–400 km/s) components, with the fast wind filling the majority of the heliosphere and the slow wind confined to within 30° of the solar equator. The slow solar wind is denser than the fast wind by a factor of approximately 3 and is considerably more variable in velocity, density, and composition. The fast wind overlies regions of low density and temperature in the solar corona—"coronal holes"—and it is now generally accepted that it has its origin in these regions of largely open magnetic field. The slow wind, by contrast, lies above brighter corona, and while its average composition indicates an origin in regions that are hotter than coronal holes, the large degree of variability in all parameters suggests that the slow wind may consist of several components with different sources.

During periods of maximum solar activity the situation is very different, with the heliosphere dominated by slow wind. Narrow streams of fast wind may be present at any latitude, so paradoxically the Earth within its magnetosphere is more likely to be bathed in fast wind at solar maximum than at minimum.

Geomagnetic disturbances and aurora on Earth are most likely to be caused by the passage of pressure enhancements in the solar wind. These can be caused by the passage of ejecta from solar eruptions or by compression regions developing on the leading edge of fast streams as the rotation of the Sun carries them under slow flow from longer longitudes (recurrent storms). In either case the disturbance will be more intense if the pressure enhancement is accompanied by a southward deviation of the magnetic field carried out by the solar wind.

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See also **Aurora; Magnetic Storms; Magnetosphere of Earth**

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SOOTY ALBATROSS

The sooty albatross *(Phoebetria fusca)* is a small and slender dark brown albatross with long narrow wings and a conspicuous white crescent above and behind both eyes. Sooty albatrosses weigh between 2 and 3.5 kg and have a wingspan of 2 m. The bill is slender with a creamy yellow-orange stripe on the lower bill. The legs and feet are a grey-mauve colour. The juveniles and immatures appear broadly similar to the adults, except that the bill stripe and eye ring are a greyer colour.

Sooty albatrosses were listed as Vulnerable in 2000, with this evaluation being revised in 2003 to Endangered on the basis of a 75% decrease in numbers over 90 years (three generations). However, the negative population trends from three sites may require this species be relisted to Critically Endangered if these trends are found to be more widespread.

Sooty albatrosses breed at five island groups in the Indian and Atlantic Oceans. This biennially breeding species is estimated to have an annual breeding population of 12,500 to 19,000 pairs, equivalent to a total breeding population of 42,000 individuals. The largest populations occur on Gough Island and Tristan da Cunha, the Gough Island population decreasing by about half in 28 years. At Marion Island the population has decreased by 25% since 1990, and the Crozet population on Possession Island has decreased by over 50% since 1980. The observed population decrease in the Indian Ocean Crozet population is a result of increases in both adult and juvenile mortality rates, with the adult mortality rates being significantly related to longline fishing effort in the ocean sectors where the birds overlap with fishing operations.

Sooty albatrosses breed on vegetated cliff ledges or steep slopes, their nesting density varying with terrain. The nests are constructed with mud and plant material, and both sexes participate in nest building. The single egg is laid in early October and is incubated alternately by both parents for 10 weeks. The chick hatches in mid-December and is brooded for 3 weeks. Chicks fledge from the nests in May when they are between 5 and 6 months old. Sooty albatrosses are generally biennial breeders with most successful adults returning to breed in the second year after success. Juvenile Sooty albatrosses generally do not return to land until they are at least 8 years of age and do not breed until 12 years.

Sooty albatrosses are dispersive and solitary at sea. During the summer breeding season their oceanic range includes the South Atlantic and southern Indian Oceans, between 35° and 50° S in subtropical and sub-Antarctic waters, particularly in the vicinity of the subtropical convergence. In winter, most sooty albatrosses are observed between 30° and 40° S in the subtropical zone, where immatures remain throughout the year. The diet includes squid, fish, carrion, and crustacea, with the proportions of each varying with location. The few observations of feeding behaviour include prey being seized at the surface, but the morphological similarity of the two *Phoebetria* albatross species would suggest that sooty albatrosses may also be accomplished diving birds.

Sooty albatrosses are known to scavenge behind longline fishing vessels and to be drowned after ingesting the baited hooks. This source of mortality has been recognised as a key threatening process for this species. Sooty albatrosses have previously been harvested for human consumption in the Tristan da Cunha group, but this practice is now illegal, and its occurrence today is considered a rare event. Introduced predators, and possibly disease, have also been identified as threats that impact on this species at their breeding colonies.

ROSEMARY GALES

See also **Albatrosses: Overview; Crozet Islands (Îles Crozet); Fish: Overview; Gough Island; Prince Edward Islands; Seabird Conservation; Seabird Populations and Trends; Seabirds at Sea; Squid**

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SOUTH AFRICA: ANTARCTIC PROGRAM

The Republic of South Africa is one of the twelve original signatories of the Antarctic Treaty and maintains a continuous scientific operation at the base Sanae, located at Vesleskarvet. The sub-Antarctic Prince Edward Islands are South African territory with a continuously manned weather station on Marion Island.

South Africa's contact with the Antarctic region can be traced back to the voyage of the Dutch East Indiaman *Maerseveen* which, after sailing from the Cape of Good Hope in 1663, reported the discovery of two islands in the southern ocean. After more than 100 years the islands were rediscovered and designated the Prince Edward Islands by James Cook in the report of his southern voyages. Until the early twentieth century they were occasionally visited by sealers. The last such activity ceased when the whaling and sealing concession to the South Africa–based sealing company was terminated by the British government in 1934.

South Africa's formal involvement in the region came when the British government transferred control of the islands to the Union of South Africa in 1950. South Africa established a permanent presence in Antarctica in 1959 when the first South African National Antarctic Expedition, led by Hannes La Grange, who had participated in the Commonwealth Trans-Antarctic Expedition, took over Norway Station on the ice shelf (70°30′ S, 2°52′ W) from the Norwegian government. In 1960 the first base Sanae (an acronym from the name of the expedition) was built on the ice shelf. Since that time South African scientific expeditions have overwintered in Antarctica every year except 1996, when the new base under construction at Vesleskarvet was still incomplete and the old Sanae base on the ice shelf was judged to be unsuitable for occupation. Other summer bases used by South African field expeditions include Borga (72°58′ S, 3°48′ W), and Grunehogna (72°02′ S, 2°48′ W).

A succession of three Sanae bases were constructed at a location (70°19′ S, 2°21′ W) on the ice shelf. Each was in turn abandoned as it sank below the surface due to accumulation of snow. In the early 1990s the decision was made to construct a new and elaborate base on the nunatak Vesleskarvet (71°40′ S, 2°51′ W). This was opened at the end of 1997. It is a modern high-tech facility, which has aroused great interest in the Antarctic community. Situated at the top of a 300 m cliff, it commands spectacular views of the Antarctic landscape.

South African Antarctic activities have been the responsibility of government ministries. They were originally managed by the Department of Transport with scientific support from the Council for Scientific and Industrial Research. Responsibility for all activities was transferred to the Department of Environment Affairs in the 1980s. In 2005 the scientific programme was transferred to the National Research Foundation, with logistics remaining with the Department of Environment Affairs and Tourism.

During overwintering the scientific programme has concentrated on the physical sciences (ionospheric and magnetospheric physics, upper atmosphere research, meteorology). There has been an ongoing summer programme in geological exploration on the continent. There is a strong programme in the biological sciences, concentrating on the islands. There is an extensive oceanographic programme undertaken from the research ship *SA Agulhas* and other vessels. The South African National Antarctic Programme is identified as a key area for research the current science policy of the South African Government.

A. D. M. Walker

See also **Antarctic: Definitions and Boundaries; Antarctic Treaty System; Commonwealth Trans-Antarctic Expedition (1955–1958); Cook, James; Prince Edward Islands**

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SOUTH GEORGIA

South Georgia is a narrow island, 100 miles (160 km) long and 1.25–20 miles (2–32 km) wide, situated between latitudes 53°56′ and 54°55′ S and longitudes 34°45′ and 38°15′ W. Approximately half its area is covered with ice and permanent snow, and many glaciers run down to the sea. The island is dominated by two mountain ranges, the Allardyce and Salvesen Ranges, with Mount Paget being the highest mountain at 9626 ft (2934 m). The coastline is deeply indented with bays and fjords, especially on the northeast side. There are about twenty small lakes, and numerous streams run down the valleys.

Offshore islands include Bird Island and the Willis Islands off the northwest tip, Cooper Island off the southeast tip, and Annenkov Island off the southwest coast. The four Shag Rocks and Black Rock lie 155 miles (250 km) to the northwest of South Georgia and the Clerke Rocks and Office Boys lie 40 miles (65 km) to the southeast.

The first sighting of South Georgia was in 1675 by the London merchant Antoine de la Roché, whose ship was blown off course while rounding Cape Horn. The second was by the Spanish ship *Léon* in 1756. The first landing was by Captain James Cook, on board *Resolution,* in 1775, during his second circumnavigation of the world. Cook landed in Possession Bay on January 17, and formally took possession in the name of King George III of Great Britain. At first, Cook and his crew thought they had discovered the conjectured Antarctic continent but later realized that they had only found an island.

The British claim to South Georgia was not consolidated until the publication of Letters Patent of July 21, 1908, when it was incorporated with parts of Antarctica as Dependencies of the Falkland Islands. A resident magistrate was appointed in 1909, and a permanent administration established at King Edward Point to oversee the whaling industry. The magistrate was sometimes assisted by a customs officer, a police constable, and other officials. An Argentine counterclaim dates from the late nineteenth century, but the first assertion of sovereignty by an Argentine president came in 1938. Argentina regards South Georgia as part of the territory "Islas del Atlantico Austral" administered from Ushuaia. South Georgia was captured by Argentine forces as a prelude to the invasion of the Falkland Islands in 1982, and they held the island for 22 days. A British army garrison was then maintained at King Edward Point until 2001, when it was replaced by the British Antarctic Survey.

In 1985 South Georgia and the South Sandwich Islands (SGSSI) became a British Overseas Territory, with the Governor of the Falkland Islands as *ex officio* Commissioner. Local administration is conducted by government officers based at King Edward Point, and the commander of the British Antarctic Survey station at King Edward Point acts as magistrate. All of South Georgia is Crown Land. Permits are required by all visitors, including cruise ships and private expeditions. There are no permanent inhabitants, but the British Antarctic Survey operates two permanently manned stations at King Edward Point and Bird Island. The former specializes in fishery research and the latter in the ecology of seabirds. The post office at King Edward Point is open on request, and mail is posted with South Georgia stamps. The South Georgia Museum, which incorporates a gift shop, was established at Grytviken in 1992 and is open all year.

South Georgia lies halfway along the Scotia Arc that runs from South America to the Antarctic Peninsula. When the Atlantic Ocean opened about 200 Ma, an arm of the Pacific Plate pushed eastwards between the South American and Antarctic Plate to form the Scotia Sea bounded by the Scotia Arc. About 35 Ma, the South Sandwich Plate started to move east and dragged South Georgia from Tierra del Fuego. The Salvesen Range has the oldest rocks on South Georgia, which are remains of the Gondwana supercontinent. Much of the remaining rock is shale and sandstone derived from sediments eroded from volcanoes that were active in the neighborhood 140–110 Ma. Fossils are rare and are mostly of marine mollusks.

A harsh climate is due to the island's position in the track of deep atmospheric depressions sweeping through the Drake Passage. The weather is generally wet and windy, but it is variable and can change suddenly to calm and warm. There can also be sudden gusts of hurricane-force winds sweeping down the mountains. The mean annual temperature is +1.8°C, with a winter mean of –1.0°C and a summer mean of +5.0°C. Snow accumulates through the winter but may melt at any time, and there may be frost and snow in the summer. The sea sometimes freezes in bays.

Fauna and Flora

South Georgia's biogeographical significance is that, although it is north of Antarctica (on the equivalent latitude to northern England and Labrador in the Northern Hemisphere), it is south of the Polar Front (previously known as the Antarctic Convergence) and so is bathed by the cold waters of the Southern Ocean. On the other hand, proximity to South America and a milder climate allow temperate plants and invertebrate animals to flourish. South Georgia is particularly noted for the large breeding colonies of seals and seabirds. These feed on an abundance of marine invertebrates, notably krill and squid. It is estimated that the seabird population consumes 7.8 million tons of food each year, of which nearly three-quarters is krill. Krill is carried in currents from the Antarctic Peninsula region and concentrated in an upwelling zone at the edge of the continental shelf off the northeast side of the island. In some years, krill fail to appear around South Georgia and the seal and seabird species that feed on it either fail to breed or suffer a huge mortality of young. There are also long-term decreases in some bird species, which are believed to be due to a decline in the krill population.

There are many colonies of penguins, including those of king, macaroni, gentoo, and chinstrap. Rockhopper and Adélie penguins have nested on occasion. King penguin colonies dominate some beaches on the northeast coast. The breeding population of 200,000 pairs is rising. There are 2.5 million pairs of macaroni penguins, mainly at the northwestern end of the island, but their numbers have decreased by half in the last 30 years. Most flying seabirds belong to the order Procellariiformes and include wandering, black-browed, gray-headed and light-mantled sooty albatrosses, northern and southern giant petrels, and a variety of smaller, burrow-nesting species. The latter include blue petrels, white-chinned petrels, South Georgia and common diving petrels, cape petrels, snow petrels, Wilson's storm petrels, and an estimated 22 million pairs of Antarctic prions. Other seabirds are the South Georgia shag, brown skua, kelp gull, and Antarctic tern. Land birds comprise yellow-billed sheathbill, the endemic South Georgia pipit (the world's most southerly songbird), South Georgia pintail (an endemic subspecies), and a few pairs of yellow-billed teal. Forty-nine species have been recorded as vagrants. Most are seabirds, but barn owl, peregrine falcon, turkey vulture, two species of swallow, and six species of shorebirds have been observed.

Whales gather in the summer months, mainly in the krill-rich zone on the northeast side of the island. They were extremely abundant before the start of Antarctic whaling a century ago, and there are signs that two of the overhunted species, the southern right whale and humpback whale, are recovering. These two species had been extensively hunted at the start of the whaling era because they are slow-moving and frequently feed near the shore. Only male sperm whales are seen around South Georgia, and other toothed whales include southern bottlenose whale and long-finned pilot whale. Killer whales are not common, but they, and sperm whales, have developed the habit of stealing Patagonian toothfish from fishing lines.

The main species of seals are southern elephant seal and Antarctic fur seal, both of which were hunted excessively in the nineteenth century but have now recovered. The fur seals returned from near extinction over the second half of the twentieth century. Breeding colonies are still increasing and spreading along the coastline, and the population now numbers several million. Elephant seals were subjected to a sustainably managed harvest during the first half of the twentieth century, and they now number over half a million. The colony of fewer than 100 Weddell seals breeding in Larsen Harbour at the southeastern end of the island is the most northerly breeding population of the species. Leopard seals are seen mainly in winter and are mostly young animals that have wandered north of the usual range.

The vegetation is related to that of southern South America but the small number of species reflects the cold climate and the difficulty of seeds crossing the open sea. There are twenty-five native species of higher plant, including six ferns, and the vegetation is dominated by tussock grass or tussac. There are also extensive stands of greater burnet, Antarctic hairgrass, tufted fescue grass, and greater and brown rushes. There are many more lower plants, including about 125 species of moss, 80 liverworts, 150 lichens, 10 algae, and 50 fungi. Coastal waters are dominated by three species of giant kelp, which form an important habitat for fishes and marine invertebrates.

The terrestrial invertebrate fauna is similarly simple and related to southern South America, although about one-third are endemic species. Free-living invertebrates number about forty species of insects, ten crustaceans, several mites, four spiders, worms, and one snail. Insects include seven beetles, including a water beetle, thirteen flies, including one that forms swarms, and a parasitic wasp. The birds and mammals are hosts to lice, mites, and fleas. The nose of the elephant seal is infested with a mite that causes the frequent snorting and thick nasal discharge associated with this seal.

Like so many other islands, South Georgia has been afflicted by alien species introduced by human agency. The whalers deliberately introduced a number of animals, including sheep and cats, but only reindeer have survived. Brown rats are widespread and abundant in the northwest and along the northeast coast, where they have had a serious effect on populations of the pipit, pintail, and small burrow-nesting petrels. There are also two small colonies of house mouse. Several species of alien invertebrate have become established, including mites, springtails, and carabid (ground) beetles. Introduced plants include dandelion, creeping buttercup, chickweed, and the grass *Poa annua*.

Expeditions

James Cook's report of "sea-bears" (fur seals) led to visits by sealers, some of whom were interested in geographical and scientific discoveries. The best-known of these is James Weddell, who published a detailed account of the island and its wildlife. In 1877–1878, the Austrian naturalist Heinrich Klutschak visited on an American sealing vessel. The island was visited in 1819 by Fabian von Bellingshausen's Russian expedition on board *Mirnyy* and *Vostok,* and a survey was made of the southern coast. The first scientific expedition to be based on land was the German International Polar Year Expedition of 1882–1883. Eleven men spent a year at Moltke Harbour in Royal Bay, where a varied scientific program was carried out and the Transit of Venus observed. The Swedish South Polar Expedition made an extensive visit over 2 months in 1902. While the ship *Antarctic* carried out a hydrographic survey, a three-man shore party carried out biological and geological investigations. The German *Deutschland* expedition under Wilhelm Filchner made three visits to South Georgia in 1911 and 1912. Moltke Harbour was reoccupied, and charting and surveying was carried out as well as extensive geological and meteorological investigations.

Much of the scientific work in the first half of the twentieth century relied on logistic assistance from whalers. The Swedish naturalists Eric Sörling and Carl Skottsberg were guests of Carl Anton Larsen in 1904 and 1909, respectively, and David Ferguson was employed by Christian Salvesen's to make a geological survey in 1912. Robert Cushman Murphy carried out ornithological studies when *Daisy* became the last old-time sealer and whaler to visit South Georgia in 1912–1913. Ludwig Kohl, who had been on the *Deutschland* expedition, and his wife Margit, one of Larsen's daughters, together with the photographer Albert Benitz, formed the Kohl-Larsen Expedition in the summer of 1928–1929. They made the first surveys of the interior of South Georgia and carried out glaciological and biological investigations. After the Second World War, C. S. Gibson-Hill and Niall Rankin made private ornithological expeditions and Duncan Carse led a series of four expeditions from 1951–1957 to make the first full survey of the island. Other biological expeditions were led by Bernard Stonehouse and Lance Tickell. From 1969, research has been carried out mainly by the British Antarctic Survey.

South Georgia is famous for the three visits by the explorer Sir Ernest Shackleton, none of which were in his original plans. In 1914, the Imperial Trans-Antarctic Expedition made South Georgia its forward base instead of the Falkland Islands. A month was spent preparing *Endurance* for the Weddell Sea, and some scientific work was undertaken. After *Endurance* had foundered in the Weddell Sea and its complement had reached Elephant Island, Shackleton and five companions reached King Haakon Bay on the southwest coast of South Georgia in *James Caird*. Shackleton and two companions then crossed the unexplored interior of the island to reach Stromness whaling station. In 1922, delays forced the Shackleton-Rowett Expedition on *Quest* to visit South Georgia rather than Cape Town. Shackleton died within hours of arriving at Grytviken, and he was later buried in the whalers' cemetery.

Exploitation

Since the island's discovery, the natural resources of South Georgia have been subjected to three forms of exploitation: sealing, whaling, and fishing. The first sealers arrived about 1786 to exploit both fur and elephant seals. Records are scant, but most sealers were British or American and operated from small vessels and shore camps. Seals on crowded breeding beaches were easily slaughtered and, when profitable markets were developed for their skins, fur seals became increasingly rare and eventually almost extinct. Elephant seals did not suffer so badly. The first peak in sealing occurred around 1800 and, after a lull, there was a second peak around 1820. After this it took longer for the seals to recover, and there was a third, smaller peak around 1870. Elephant sealing was also undertaken by the whaling company at Grytviken from 1904 to 1964. The harvest was regulated by the government, and the production of high-quality oil was a significant factor in the continued profitability of the whaling station.

The whaling industry started in 1904 when Larsen established the first whaling station at Grytviken. The success of this operation attracted other companies, and within 10 years shore stations and floating factories were operating in seven bays, and there were sometimes more than 1000 men employed. Until 1919 whaling took place throughout the year but thereafter it was limited to the summer months. Profits were very good and demand for whale oil increased during the First World War. However, the shore stations began to have difficulties during the 1920s when pelagic factory ships started to operate on the high seas. There followed overproduction of oil, and only two stations survived: Grytviken and Leith Harbour. Husvik reopened for a few years after the Second World War when oil prices were high, but whales became increasingly scarce, and whaling ceased on South Georgia in 1965.

From the start, there was concern that whales were being overexploited and, in 1918, the British government established the Discovery Committee to investigate the Southern Ocean and the biology of its whales to provide information necessary for the sustainable management of whale stocks. Whales were studied at Grytviken by a team of scientists based in a laboratory, Discovery House, at King Edward Point. The carcases of 1683 whales were studied to yield information on growth, diet, and breeding. Unfortunately, the findings of these studies were not applied to the regulation of whaling because the industry was controlled by economic interests.

Large-scale fishing was started by the Soviet bloc around South Georgia in 1969–1970, and within a very few years, stocks of marbled rock cod had been so seriously depleted that they have never recovered. Since then fisheries have developed for krill, mackerel icefish, and, most importantly since the 1990s, Patagonian toothfish. These fisheries were brought under control in 1993 when the Government of South Georgia created a Maritime Zone that extends 200 nautical miles around the coastline of South Georgia, the South Sandwich Islands, and outlying rocks. Within this area, management is based on measures laid down in the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR). The CCAMLR Commission monitors fish populations in the Southern Ocean and sets a quota, called the Total Allowable Catch (TAC), for each exploited fish species within designated blocks. The relevant blocks for the South Georgia Maritime Zone are 48.3 and 48.2 (48.4 for the South Sandwich Islands).

The South Georgia government awards licenses to fishing vessels, which must comply with local regulations for the management of fisheries. These are monitored and enforced by government officers and by fisheries' protection vessels. Prosecution for infringement may result in heavy fines. The bycatch of albatrosses and other seabirds in the toothfish fishery has been of great concern. The numbers of breeding albatrosses on South Georgia have decreased considerably in recent years. However, the stringent application of mitigation techniques, such as deploying streamers over lines as they are shot, has effectively eliminated the bycatch in South Georgia waters.

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See also **Albatrosses: Overview; Antarctic Fur Seal; Antarctic Prion; Bellingshausen, Fabian von; Chinstrap Penguin; Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Cook, James; Discovery Investigations (1925–1951); Fish: Overview; Fisheries and Management; Gentoo Penguin; German South Polar *(Deutschland)* Expedition (1911–1912); Gondwana; Humpback Whale; Imperial Trans-Antarctic Expedition (1914–1917); Insects; International Polar Years; Islands of the Scotia Ridge, Geology of; Kelp Gull; King Penguin; Larsen, Carl Anton; Macaroni Penguin; Northern Giant Petrel; Parasitic Insects: Mites and Ticks; Penguins: Overview; Plate Tectonics; Polar Front; Russian Naval (*Vostok* and *Mirnyy*) Expedition (1819–1821); Seabird Conservation; Sealing, History of; Seals: Overview; Shackleton, Ernest; Shackleton-Rowett Antarctic Expedition (1921–1922); Southern Elephant Seal; Southern Giant Petrel; Southern Right Whale; Squid; Swedish South Polar Expedition (1901–1904); Terrestrial Birds; Toothfish; Tourism; Volcanoes; Weddell, James; Whales: Overview; Whaling, History of; Zooplankton and Krill**

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SOUTH KOREA: ANTARCTIC PROGRAM

A few pioneer polar scientists working with Korea Ocean Research and Development Institute (KORDI) formed a task force on Antarctic programs and started to make plans for Antarctic research, infrastructure, and governmental framework in the mid-1980s. They established the Polar Research Division within KORDI in 1987, launched the Korea Antarctic Research Program (KARP) in 1987, and dispatched the first Korean Antarctic Scientific Expedition Party in 1988.

Building on the first governmental framework and Antarctic research plan, Korea joined the Convention on the Conservation of Antarctic Marine Resources (CCAMLR) in 1985, acceded to the Antarctic Treaty in 1986, and became an Antarctic Treaty Consultative Party (ATCP) in 1989. One of the greatest achievements of those pioneer polar scientists was to successfully push forward their plan of the first Korean Antarctic Station. In 1988, Korea built the first Korean Antarctic Station on King George Island, which later played a critical role in the success of Antarctic science programs both on land and at sea.

After setting up the first Korean Arctic Station on Svalbard in 2002, the Polar Research Division of KORDI became the Korea Polar Research Institute (KOPRI), an independent research body in 2004. As KOPRI is preparing to expand its role in international polar science community, it is in the process of conducting a wide variety of Arctic and Antarctic research with international institutes, starting to construct a new icebreaker, and planning to build a second Antarctic station.

Korea Polar Research Institute (KOPRI)

In 1987, the Polar Research Laboratory was established by a group of polar scientists within KORDI and was initially led by Dr. Byong-Kwon Park, known as the founder of the Korean Polar Research Program. They dispatched seventeen Antarctic expedition parties between the inauguration of the Antarctic King Sejong Station in 1988 and 2004. Later the Polar Research Laboratory was expanded to a research division in KORDI.

In 2004, the Polar Research Division was separated from KORDI and became KOPRI, an independent research body. The first director of KOPRI was Dr. Yeadong Kim, leader of the pioneering group of polar scientists in Korea. KOPRI consists of the Planning and Administration Division and two research divisions: Polar Environmental Research and Polar Applied Science Division.

KOPRI aims to promote comprehensive polar-region scientific research in cooperation with Korea National Committee on Polar Research (KONPOR), to administer scientific programs, and to provide logistic support. The missions of KOPRI are (1) to promote and support polar scientific research, survey, and long-term observations addressing key issues of global concern, (2) to conduct logistic support for research and station maintenance, (3) to develop research infrastructure, and (4) to assist governmental decision making on policies related to the polar regions. Currently, major research activities conducted by KOPRI scientists are (1) geologic/geophysical studies on tectonic setting, tectonic evolution, and crustal structure of Antarctica, (2) studies on paleoclimatic change, (3) past climatic signature in snow and ice, (4) oceanographic studies on Antarctic marine life resources and ecosystems, (5) Antarctic marine living resources program, (6) polar atmospheric research, and (7) optical aeronomy studies and environmental monitoring at Antarctic/Arctic stations.

KOPRI will endeavor to make a unique contribution toward finding solutions to global concerns, including environmental change. KOPRI scientists continue to collaborate with colleagues from international institutes in various global monitoring programs such as cooperation with International Seismological Center, World Meteorological Organization, and global sea-level observation.

KOPRI actively participates in various committees and working groups of international organizations to share benefits from scientific outcomes by enhancing internationalization of research programs. KOPRI became the twenty-second member of the Scientific Committee on Antarctic Research (SCAR) in 1990, and joined the Council of Managers of National Antarctic Programs (COMNAP) and the International Arctic Science Committee (IASC) in 2002. Also as a founding member of Asian Forum of Polar Sciences (AFOPS), KOPRI keeps contributing toward the development of Asian polar community through a commitment to AFOPS and a leading role in activities of its working groups.

Antarctic "King Sejong" Station

On February 17, 1988, King Sejong Station began functioning as a permanent research station for KARP. King Sejong Station is located on the Barton Peninsular, King George Island, and its coordinates are 62°13′ S, 58°47′ W. The station consists of ten buildings for accommodations and facilities and two observatories for research after extension in 1991 and 2000. The location of the station is best for detecting environmental changes and for studying the behavior of high-energy cosmic particles from outer space. The station is also equipped with geophysical and GPS observatories. The station accommodates two major expeditions every year, a summer expedition and an overwintering research party.

Arctic "Dasan" Station

Dasan station is located at Ny-Alesund (78°55′ N, 11°56′ W) on the high Arctic island of Spitsbergen, Svalbard. Dasan station was established on April 29, 2002. The Station buildings and facilities are leased from a Norwegian company, and they accommodate laboratory space with some scientific equipment, computers, internet connection, and communication facilities. The location of the station is particularly suitable for ecological research, glacial/periglacial geomorphology, hydrology, and atmospheric chemistry.

Korea National Committee on Polar Research (KONPOR)

Following the first governmental framework and Antarctic research plan, Korea established the Korea National Committee on Antarctic Research (KONCAR) in 1987. KONCAR expanded to the Korea National Committee on Polar Research (KONPOR) as KOPRI established Arctic Dasan Station and joined the International Arctic Science Committee (IASC) in 2002. The mission of KONPOR is to enhance and expand scientific programs in polar region through national support and guide. KONPOR is also responsible for reviewing scientific research programs and intermediate and long-term plans conducted and prepared by KOPRI.

YEADONG KIM

See also **Antarctic Treaty System; Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Council of Managers of National Antarctic Programs (COMNAP); King George Island; Scientific Committee on Antarctic Research (SCAR); World Meteorological Organization**

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SOUTH ORKNEY ISLANDS

The South Orkney Islands (latitudes 60°50′ to 60°83′ S, longitudes 44°25′ to 46°25′ W) were discovered and charted on 6 December 1821 by George Powell and Nathaniel Palmer on the sealers *Dove* and *James Monroe*. Powell claimed the islands (the Powell Group) for Great Britain, naming the largest Coronation Island for George IV's coronation. James Weddell visited the islands in 1823, gave the archipelago its present name and renamed some of the islands.

The islands held little interest for the sealers, and only six visits are recorded before the Scottish National Antarctic Expedition of 1902–1904, led by William Speirs Bruce aboard the *Scotia,* surveyed the islands, reverted some of Weddell's name changes and established a meteorological station at Scotia Bay on Laurie Island during March 1903. In 1908, the South Orkneys became part of the British Crown colony of the Falkland Islands. Argentina also claims the South Orkneys (Orcadas Islands), but the archipelago is now subject to the Antarctic Treaty (1959) under which all territorial claims south of 60° S are set aside.

Floating whaling stations visited the South Orkney Islands annually from 1907–1908 until 1914–1915 taking some 2029 whales. During 1912–1913, the whaling captain Petter Sørlle charted the island group, naming the small island south of Coronation Island after his wife, Fru Signy Sørlle. In the early 1920s a licence was granted to Tønsberg Hvalfangeri (Norway) to establish a shore whaling station on Signy Island in Factory Cove, the only reasonable anchorage around the island. This station operated but briefly, giving way to floating factory ships anchored in the Cove, processing 3500 whales over the period 1921–1929.

With the onset of pelagic whaling Factory Cove was abandoned until 1947 when the Falkland Islands Dependencies Survey (FIDS) established a research station there. A four-man station complement began a science programme that continues to the present day, with FIDS ultimately becoming the British Antarctic Survey (BAS) in 1962. Bruce's old meteorological station on Laurie Island (renamed Orcadas Station in 1951) has been continuously operated by Argentina since 1904 and is the oldest continuously staffed research station in the Antarctic. Its unique meteorological record, extending over 100 years, has provided valuable evidence of significant climate warming in the region.

The South Orkney Islands have a total surface area of about 620 km, and many have an ice sheet. The archipelago comprises four main islands of which Coronation Island is the largest (and most ice-covered) with a high point (Mount Nivea) of 1266 m. Laurie Island, the second largest, is the easternmost of the islands with terrain rising to over 400 m characterised by bold headlands, precipitous cliffs, and deep glacier-filled valleys. There is very little flat ice-free land, and the only landing beach of any size is at Scotia Bay. The other islands are the smaller Signy Island and Powell Island and a number of very small rocky islands (notably the Saddle Islands). Signy Island (60°43′ S, 45°38′ W), scientifically the best known of the group, has approximately 30% of its area under an ice sheet, though this has been in significant retreat since the 1960s. In common with the other islands, Signy Island is formed primarily of metamorphic rocks comprising an interlayered sequence of mica-schist (gneiss), marble, and amphibolites. Ridges of the igneous rock, dolorite, are visible on Coronation Island.

The climate of the South Orkneys is generally cold, wet, and windy. The mean annual temperatures are around –4°C and mean monthly temperatures are above 0°C for at least one month per year. In winter, mean monthly minimum temperatures are around –17°C, and temperature extremes of +25°C and –44°C have been recorded on very rare occasions. The South Orkneys lie toward the outer edge of the maximum extent of Antarctic winter sea ice so there is substantial variability in the sea-ice coverage within the island group each year.

The warm northerly "Fohn" winds sweeping down from Coronation Island have promoted extensive deglaciation on Signy Island, in contrast to the other islands, allowing the creation of many lakes and pools and a greater focus for wildlife. Extensive vegetation and vast numbers of nesting birds occur together with substantial seal colonies. The dominant plants on the islands are mosses (around fifty species) and lichens (about 120 species) with lesser numbers of liverworts (about twelve species) and two flowering plants. Mosses carpet much of the lower lying wet habitats though large areas of moss peat banks around 1 m in depth and up to 5500 years old occur on Signy Island. Higher ground comprises more sparsely vegetated fellfield (sorted, patterned ground) dominated by lichens, and occasional low moss cushions whilst a range of colourful lichens cover the large boulders. In areas where birds, and more particularly seals, are present in large numbers, green mats of the alga *Prasiola* cover most damp surfaces.

The largest terrestrial animals are Acarid mites (c. 1 mm) preying on Collembola (springtails), which graze microalgae, fungi and plant cells. Such small invertebrates have developed physiological strategies for surviving freezing and desiccation. There are no native winged insects or spiders on the South Orkney Islands.

The seasonally ice-covered freshwater environments (some over 7000 years old) range from nutrient-poor lakes through to grossly enriched seal wallows. Extensive beds of aquatic mosses and, more often, cyanobacterial mats cover the bottom sediments. The largest animal is the herbivorous "fairy shrimp," *Branchinecta gainii,* which grazes on the cyanobacterial mats. The zooplankton is dominated by a tiny red copepod, *Boeckella poppei.*

The coastal marine environment is rich and varied with well-colonised rock faces and shallow sandy areas that have been extensively studied and documented. Whilst initially, commercial exploitation of several fish species (notably Nototheniids, "Antarctic cod") was undertaken in the South Orkney Islands, commercial trawling is now restricted to a small krill fishery. Sixteen species of bird breed on the island, notably four species of penguin (the very numerous Adélie and chinstrap penguins, and gentoo and macaroni penguins). Around 2000 elephant seals arrive at Signy Island in spring, and a number of pups are born each year. At the end of winter Weddell seals pup on the sea ice around the island. Crabeater seals are also present at this time, and leopard seals occur around the penguin colonies in summer. Since the 1970s fur seals *(Arctocephalus gazella)* have arrived in increasing numbers in late summer, peaking at around 20,000 individuals.

J. Cynan Ellis-Evans

See also **Adélie Penguin; Algae; Algal Mats; Antarctic Fur Seal; Argentina: Antarctic Program; British Antarctic Survey; Bruce, William Speirs; Chinstrap Penguin; Crabeater Seals; Gentoo Penguin; Leopard Seal; Macaroni Penguin; Mosses; Palmer, Nathaniel; Scottish National Antarctic Expedition (1902–1904); Weddell Seal; Weddell, James; Whaling, History of**

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SOUTH POLAR SKUA

The South Polar skua *(Catharacta maccormicki)* is the southernmost-recorded bird species—they have been seen at Amundsen-Scott Base at the South Pole. Circumpolar in distribution, they breed around the coast of Antarctica and the sub-Antarctic islands. They are even found nesting long distances inland on nunataks near remote colonies of snow petrels *Pagodroma nivea*. At sea, South Polar skuas are primarily seen over the Southern Ocean, but they have the longest migration of all the southern skuas. Nonbreeding birds and juveniles migrate north into the northernmost reaches of the Atlantic and Pacific Oceans and at least as far north as the equator in the Indian Ocean. One South Polar skua has been recorded from Greenland.

Skuas as a group diverged from the gulls about 10 Ma, but their similarities still cause debate about whether they should be considered a separate family, the Stercorariidae. Within the family, there is further debate regarding the number of species. In all accounts, however, the South Polar skua is separated from the various brown, Sub-Antarctic or Antarctic skuas. Their breeding distribution extends north on the Antarctic Peninsula and the South Shetland Islands where they overlap with the breeding distribution of the Sub-Antarctic (brown) skua. Where their breeding populations overlap (e.g., Anvers Island) mixed pairs occur regularly, and they produce hybrid offspring. Mixed species pairs and hybrids have also been reported from the French station at Dumont d'Urville in East Antarctica.

The South Polar skua is considerably smaller than the Subantarctic skua, but is about the same size as the Falklands, Tristan, and Chilean skuas. Compared with the Subantarctic skua, the South Polar skua has a slighter body with shorter legs and smaller head and bill. With a wingspan of 130–140 cm and mass of 900–1600 g, they are still formidable predators. Their close relationship with gulls is clear from their general body shape and size, however, skua bills are more strongly hooked than those of the gulls and they have strongly curved claws on their webbed feet. The wings, back and tail of South Polar skuas are dark brown, and they have the characteristic white flashes at the wrists. Otherwise, they are highly variable with pale, intermediate, and dark color morphs. The dark birds are most common in the Antarctic Peninsula, and they have a dark head, neck, and body. These dark morphs may be difficult to distinguish from the similar Sub-Antarctic skua, but the nape is generally paler, so there is usually a contrast between the nape and the darker back. In addition, many show pale feathers at the base of the bill. The pale and intermediate morphs are more common in continental populations. In these the head, neck, and body vary from a slightly buffy white to a medium brown color. In all cases, however, the lighter feathers of the neck and body contrast distinctly with the darker wings.

South Polar skuas are predators and scavengers. They also steal food from other species as they return from their own foraging trips. This kleptoparasitic behaviour led Herbert Ponting, the photographer on Scott's Terra Nova Expedition, to dub them "Buccaneers of the South." They prey on storm petrels and other petrels and on the eggs and chicks of penguins and other seabirds. They even eat each other's eggs and chicks when opportunities arise. Around most of their breeding areas on the continent, the South Polar skua is the top avian predator and accounts for considerable mortality of penguin and petrel eggs and chicks. In the northern parts of their breeding distribution, they are supplanted by their larger cousins the Sub-Antarctic (brown) skua. Where they co-occur, Subantarctic skuas are able to occupy all the territories that have access to penguin colonies, and the South Polar skuas are forced to go to sea to fish for their food, especially Antarctic silverfish *(Pleurogramma antarctica)*. Nonbreeding and migrating birds forage at sea for fish and are known to scavenge around fishing boats. Where it is available, South Polar skuas will scavenge around Antarctic stations or camps for food scraps, and until recent changes in environmental policies, some skua populations were larger than natural conditions would allow because of the extra food obtained from around stations.

After their long migration, South Polar Skuas return to the Antarctic in late October to early November to breed. They breed in loosely structured colonies that are typically associated with colonies of other breeding seabirds. They nest in the highest concentrations around large penguin colonies, but not all nesting skuas are associated with penguins or petrels. They also nest in lower densities in many ice-free areas where they go to sea to forage. South Polar skuas are faithful to their mates and territory sites, so there is little turnover of adults on territories from year to year. Their mating patterns appear to be very stable, but extra-pair matings have been observed. In many cases, the adults arrive before the snow cover is gone, so they spend several weeks courting and defending their territory. At this time, the males do most of the foraging at sea and then feed the females when they return. The male will make several nest scrapes in the territory, and the female will eventually settle on one of them where she will normally lay two eggs 2–4 days apart.

South Polar skuas are strong and agile flyers, and they are extremely aggressive in defense of their territories. The characteristic territory defense display is the "long call." One or both of the adults stand up tall and hold their wings high behind their back. They then throw their head back and with mouth wide open they call loudly: "ha...ha...ha...ha." If that is insufficient to keep intruders off the territory, they fly up and give chase. These chases can become impressive aerial combats with high speed aerobatic maneuvers and vicious attacks. At times they seem more motivated by territory defense and leave the eggs or chicks unguarded for long periods. Consequently, the loss of eggs to other skuas is often a major cause of nest failure.

When they are off their territory, skuas are very social. There is usually a nearby lake or pond that they use as a bathing site where many birds come together to bathe and preen. Alternatively, there may be a "club" site without the usual bathing pond. There is little aggressiveness at these sites, and young nonbreeders have a chance to socialize without the usual aggressiveness associated with territories.

The South Polar skua is also well known for the frequency of siblicide by the nestlings. Because the eggs are laid several days apart, they hatch 1–3 days apart. The first chick has a size advantage on its younger sibling, and in many populations the older chick will attack its younger sibling. The older chick sometimes kills its sibling outright, but more often they intimidate the younger chick so that it is unable to feed adequately and dies as a result. The chicks in about 5% of bird species in the world show similar aggressiveness, but the South Polar skua is the only species where the parents intervene in the sibling fights. The surviving chicks depart in March and roam the ocean for several years. Most young do not begin to arrive back at their breeding colonies until they are 3 years old. They make attempts at finding a territory, but with the lack of experience and the tightly held territories, they normally do not succeed until they are 6 or 7.

With an estimated population of 5000–8000 pairs of South Polar skuas, they are the least common of all birds species breeding in Antarctica. Their reproductive success is variable and dependent on local conditions, but they are widespread and not globally threatened.

GARY D. MILLER

See also **Amundsen-Scott Station; Antarctic Peninsula; British Antarctic *(Terra Nova)* Expedition (1910–1913); Chilean Skua; Fish: Overview; Kelp Gull; Penguins: Overview; Photography, History of in the Antarctic; Seabird Conservation; Seabird Populations and Trends; Skuas: Overview; Snow Petrel; Sub-Antarctic Skua**

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SOUTH POLE

The South Pole—or South Geographic Pole—is the Earth's southernmost point, at latitude 90° S, where the meridians of longitude converge. The South Pole marks the southern end of the Earth's axis of rotation and is generally considered in a fixed location, although its position actually shifts slightly as the Earth wobbles on its axis (known as the Chandler wobble) over a period of about 14 months.

At the South Pole, the Sun rises on or about September 21, the vernal equinox, and does not set again until about March 21, the autumnal equinox. The Sun's maximum elevation above the horizon is 23.5° on the summer solstice (about June 21). During the period of its ascent, the Sun daily makes a 360° circuit around the horizon.

The South Pole is located on the South Polar Plateau at an elevation of approximately 9300 feet (2835 meters). Amundsen-Scott, a United States scientific station, is located very close to the South Pole, and from there the Plateau is generally featureless as far as can be seen, other than for sastrugi. The winter low temperature recorded at the station was –82.8°C, and the summer high temperature –13.6°C. The wind averages 12.1 miles/h (5.5 m/sec). The closest land is actually straight down through the ice, approximately two miles (3.2 km) away. On the surface, the closest rock is Mount Howe, a nunatak approximately 181 miles (290 km) distant. The closest coastline is approximately 790 miles (1270 km) away.

The first individuals to reach the South Pole were the five members of a Norwegian party led by Roald Amundsen, who did so on December 14, 1911. A little more than a month later, on January 17, 1912, a British party led by Robert Falcon Scott reached it as well. The first flight over the Pole, on November 29, 1929, was accomplished by four men, the leader of the party being Richard E. Byrd. The first plane to land at the South Pole was piloted by Conrad S. Shinn, as part of Operation Deep Freeze, on October 31, 1956. A month later, construction of Amundsen-Scott station began in preparation for the International Geophysical Year. The next year, a party became the first to winter at the South Pole, under the scientific leadership of Paul Siple. As part of the Commonwealth Trans-Antarctic Expedition, a group under Sir Edmund Hillary became the first to reach the Pole in motorized transport—and the first to do it overland since Scott—on 4 January 1958. Fifteen days later, they were joined by Vivian Fuchs' part of the expedition, which then continued across the continent. In recent years, many adventurers have trekked to the South Pole, the first solo effort being by Erling Kagge in 1993.

In addition to the South Geographic Pole, three other poles are recognized in the Antarctic. The South Magnetic Pole is the point in the Southern Hemisphere where a dip needle (a freely suspended magnet on a horizontal axis) points towards the Earth's centre. The south-seeking end of a compass needle or any magnet is attracted toward this Pole. Both the North and South Magnetic Poles wander as the Earth's magnetic field changes. The general region of the South Magnetic Pole was first reached at 72°15′ S, 155°16′ E (in Victoria Land) on January 16, 1909, by a party of T. W. Edgeworth David, Douglas Mawson, and Alistair Mackay on Ernest Shackleton's British Antarctic Expedition. It was next approached from the north in December 1912 by a party under Robert Bage on Mawson's Australasian Antarctic Expedition, who estimated it to be at 71° S, 150° E. It has subsequently migrated north and is currently located off the coast of Terre Adélie, in the area of 65° S, 138° E.

The South Geomagnetic Pole is the southern end of the axis of the Earth's geomagnetic field, from which emerge the lines of force that extend far into space, forming the magnetosphere. Convergent lines above the Pole, where electron flux from the Sun is concentrated, create an intense magnetic field in a ring of 23° in the stratosphere, meaning that displays of the Aurora Australis are concentrated in this area. The South Geomagnetic Pole lies at 78°30′ S, 110°00′ E, on the plateau of Greater Antarctica. This area was first attained by a Soviet Antarctic expedition in 1957, the goal of which was to establish Vostok Station, which is situated nearby.

The Pole of Inaccessibility is defined as the point farthest from any coast, and, in theory, therefore the most difficult location to reach. It lies at 77°15′ S, 104°39′ E for the contiguous continent (also close to Vostok Station) or at 85°50′ S, 65°47′ E for the continent and ice shelves, a position south of the Prince Charles Mountains. The latter, at an elevation of

12,150 feet (3700 meters), was first reached on 13 December 1958 by a Soviet expedition, which established a temporary scientific station.

BEAU RIFFENBURGH

See also **Adventurers, Modern; Amundsen, Roald; Amundsen-Scott Station; Antarctic: Definitions and Boundaries; Aurora; Australasian Antarctic Expedition (1911–1914); British Antarctic *(Nimrod)* Expedition (1907–1909); British Antarctic *(Terra Nova)* Expedition (1910–1913); Byrd, Richard E.; Commonwealth Trans-Antarctic Expedition (1955–1958); David, T. W. Edgeworth; Fuchs, Vivian; Hillary, Edmund; International Geophysical Year; Magnetosphere of Earth; Mawson, Douglas; Norwegian *(Fram)* Expedition (1910–1912); Scott, Robert Falcon; Shackleton, Ernest; Siple, Paul; United States (Byrd) Antarctic Expedition (1928–1930); Vostok Station**

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SOUTH SANDWICH ISLANDS

The South Sandwich Islands are an isolated chain of eleven volcanic islands lying between 56° and 60° S latitude and 26° and 28° W longitude, in the South Atlantic sector of the Southern Ocean. Being north of 60° S, the islands do not come under the Antarctic Treaty, and they are administratively one of the British Overseas Territories. The eight southern islands were discovered in 1775 by James Cook (Britain), and the three northern islands in 1819 by Fabian von Bellingshausen (Russia). Until the mid-twentieth century, human involvement was limited mainly to poorly documented activities of sealers and whalers. Landings on some islands were not achieved until the early 1950s, and the islands continue to be visited rarely. The only attempts at coordinated topographic and scientific surveys have been by British expeditions in 1930, 1964, and 1997. Small huts were built on Thule Island in 1955 and 1976, in pursuance of Argentina's political claim to territory in the South Atlantic, contested by Britain. Apart from a small refuge hut, the buildings were destroyed by a British naval vessel following the Falklands War in 1983.

Snow and ice almost wholly cover each island except for the four smallest islands, which are largely ice-free. They are the summit expressions of seven major submarine volcanoes 2.5–3.5 km high, with basal diameters of 30–50 km, which rise from the sea floor to a maximum height of 1370 m above sea level. Ten islands form a simple north–south-orientated arc, but one (Leskov Island) is situated about 55 km off-axis to the southwest. They are small, ranging from 2 to 12 km in diameter, and entirely volcanic, dominated by basalt and andesite lavas. Volcanic ashes, formed in explosive eruptions, are uncommon, although the South Sandwich Islands have been the most prolific contributor of ash to the East Antarctic Ice Sheet. Summit calderas (caused by collapse into a lava chamber) are present on several of the islands, and a 5 km-wide submarine caldera between Thule and Cook islands was discovered in 1997. All of the islands are young (less than 3 million years) and eruptions have been observed on most. Protector Shoal, a shallow seamount situated 56 km northwest of Zavodovski Island, erupted rhyolite pumice in 1962. Small persistent lava lakes are frequently present in summit craters on Montagu and Saunders islands. Montagu Island, with no previous record of historical eruptions, began a long-lived eruption in late 2001; it was still erupting in June 2005.

The South Sandwich Islands are within the maritime Antarctic biogeographical zone. Five species of penguin (Adélie, gentoo, chinstrap, macaroni, and king) breed in the islands, but the chinstrap is the most numerous by far. King penguins are uncommon and confined to Zavodovski and Candlemas islands. Other bird species recorded breeding include giant petrel, Antarctic skua, Cape petrel, kelp gull, Wilson's storm petrel, blue-eyed shag, and Antarctic tern. Numerous albatross species have been observed offshore. Only fur seals and elephant seals are known to breed on the islands, but Weddell, crabeater, and leopard seals are present in small numbers. Whales regularly occur, mainly humpback but also minke, southern right, southern bottlenose, and other fin whales. The terrestrial invertebrate fauna consists of relatively few species of arthropods, nematodes, tardigrades, and rotifers; a springtail species and possibly two species of enchytraeid worm discovered in 1997 were previously unrecorded from the maritime Antarctic.

Most snow-free areas are spectacularly barren of vegetation. Only a small number of species is present, including lichens, mosses, algae, and rare small stands of grass *(Deschampsia antarctica)*. Conversely, the warm, moist conditions provided by the volcanic fumaroles support a strikingly more luxuriant plant cover. These show a concentric zonation of plant communities associated with the outward-decreasing temperature gradients, and some vegetation types are restricted to the fumaroles.

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See also **Adélie Penguin; Albatrosses: Overview; Antarctic Fur Seal; Antarctic Tern; Bellingshausen, Fabian von; Cape Petrel; Chinstrap Penguin; Cook, James; Cormorants; Gentoo Penguin; Humpback Whale; Kelp Gull; King Penguin; Macaroni Penguin; Nematodes; Rotifers; Russian Naval (*Vostok* and *Mirnyy*) Expedition (1819–1821); Southern Elephant Seal; Southern Giant Petrel; Springtails; Tardigrades; Volcanic Events; Volcanoes; Wilson's Storm Petrel**

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SOUTH SHETLAND ISLANDS

The South Shetland Islands are a group of eleven large islands and nine islets, situated at the western extremity of the South Scotia Ridge and extending over a total distance of about 500 km. They lie on the southeast side of Drake Passage, about 700 km south of Tierra del Fuego and about 100 km off the northwest coast of Graham Land (northern Antarctic Peninsula). The group comprises two island clusters: a main southwest group extending 250 km between Low and Smith islands and King George Island; and the Elephant and Clarence Island Group in the northeast, separated from King George Island by a gap of about 90 km.

William Smith discovered the islands on February 18, 1819, in the brig *Williams* during a voyage between Buenos Aires and Valparaiso, making them the first part of Antarctica (south of 60° S) to be formally discovered. Smith returned to the islands and landed at North Foreland, the northeastern extremity of King George Island, on October 17, taking possession in the name of King George III of Great Britain and calling the land New South Britain, then New South Shetland. The remains of a Spanish 74, *San Telmo,* with 644 hands, which was last seen on September 4, 1819, drifting rudderless and dismasted at 62° S following a storm, were subsequently discovered at Cape Shirreff, Livingston Island. The *San Telmo* crew were conceivably the first people to live and die in Antarctica, although no human remains attributable to the ship have been discovered. Joseph Herring, the English mate on the Argentine sealer *Espirito Santo* (a British charter), landed on one of the islands and took possession of "the entire archipelago" on December 25, 1819. Edward Bransfield, RN, with William Smith, landed in King George Bay (probably at Turret Point) on January 22, 1820, where he again formally took possession for Great Britain. Bransfield also produced the first charts of the islands and (on January 30 and 31) saw the north coast of Graham Land and d'Urville Island, between 63° S and 64° S. This was one of the first two authentic sightings of the Antarctic mainland. Bransfield also landed at Cape Bowles, southernmost Clarence Island, on February 4, 1820, and claimed the Elephant and Clarence Islands Group for Great Britain. A letters patent of July 21, 1908, consolidated the earlier British claims to the South Shetland Islands as Dependencies of the Falkland Islands. However, conflicting overlapping territorial claims to the South Shetland Islands (and Antarctic Peninsula) have subsequently been maintained by Great Britain, Argentina, and Chile. They were advanced by Argentina in 1925–1927, 1942, 1946, and 1948, and for the first time by Chile in 1940.

The commercial exploitation of the South Shetland Islands took place immediately after their discovery, with visits by sealing vessels from the United States, Argentina, and Great Britain. At least ninety-one vessels were recorded working in the islands in 1821–1822 and, by the end of that season, the valuable fur seal population was almost completely exterminated and has never recovered. Several of the islands still contain low stone-wall remnants of small, originally canvas-roofed sealing shelters. Human skeletal remains from the period have been unearthed at Cape Shirreff (Livingston Island), Desolation Island, and Deception Island. That at Cape Shirreff consisted of the skull of a South American native Indian, supposedly female. Uniquely for Antarctica, stone spearheads were dredged from sediment in Admiralty Bay (King George Island) and Discovery Bay (Greenwich Island). The possibility that the spearheads were proof of an indigenous population of Indians who reached the islands 1000–2000 years ago from Tierra del Fuego has been discredited. Sealer artefacts recovered from caves and huts include timbers, seal and penguin bones, a pig's mandible, a metal gaffe, iron nails, blubber lamps, bottle glass, leather boots, sealskin moccasins, pieces of cloth and canvas, a cloth waistcoat, inscribed whale vertebra, metal knives, a wooden knife sheath, a clay pipe bowl, wax, and fire hearths. Sealing continued sporadically until 1828, and it was during that period that the coasts and harbours of the islands became well known. A brief revival took place between 1871 and the end of the century, when commercial activity then shifted to hunting whales, based mainly at Deception Island and King George Island (Admiralty Bay).

Several scientific and exploring expeditions visited the islands, mainly from the late 1880s, but few paused long enough to make more than cursory observations. Two important exceptions are the first scientific expedition to Antarctica, by HMS *Chanticleer* (1828–1831; Captain H. Foster), during which magnetic observations were made and Earth's gravity was measured on Deception Island (hence Pendulum Cove, named in honour of the gravity experiment); and the geological observations of several islands by David Ferguson during a whaling expedition in 1913–1914. However, the earliest accurate geological observations of any part of Antarctica were by Midshipman C. W. Poynter, RN, who on January 22, 1820, correctly deduced the youthful volcanic origin of Penguin Island. The survivors of Sir Ernest Shackleton's Imperial Trans-Antarctic Expedition (1914–1917) reached Elephant Island in April 1916, from where they were rescued by the Chilean tug *Yelcho* in August later that year. For logistical reasons, most scientific investigations in the islands were of limited geographical extent, and the first attempts at region-scale scientific surveys did not take place until 1965–1966 (geomorphology, botany), 1970–1971 (botany), and 1974–1976 (geology) (by the UK).

The first permanent scientific stations in the region were established on Deception Island in 1944, and King George Island in 1948 (by the UK). That on Deception Island included the first snow-free aircraft runway in Antarctica and hosted a British aerial survey expedition in 1955–1957 (FIDASE); most of the buildings were damaged or destroyed by volcanic eruptions on the island in 1967 and 1969, and the base was abandoned. Other scientific stations were established between the late 1940s and early 1960s on King George Island (Chile, Russia), Deception Island (Argentina, Chile), Greenwich Island (Chile) and Half Moon Island (Argentina), together with a few small huts *(refugia)* that were typically only occupied briefly for part of a single summer. Poland built a station on King George Island (Point Thomas) in 1978, and, because of the presence of numerous easily accessible snow-free coastal sites with running water, there was a further flurry of station building in the late 1980s and 1990s, by Bulgaria, Spain, Brazil, Ecuador, China, Uruguay, and Peru, almost all on King George Island. As a result, the South Shetland Islands contain the greatest number of scientific stations in any region of Antarctica.

The South Shetland Islands consist of two physiographic types. Most are low ice domes that rise gently to about 500 m, encircled by 30 m-high ice cliffs and infrequent small headlands that are briefly snow-free during the short austral summer. The coasts of King George and Livingston islands are indented by deep fjords (e.g., Admiralty Bay, False Bay). Other islands are considerably more mountainous and rise locally to more than 2000 m in jagged snow-clad peaks. The latter include Elephant Island, Clarence Island, Smith Island, and parts of Livingston and Greenwich islands. At 2103 m, Mount Foster (Smith Island) is the highest peak. The island with the least snow cover is Deception Island, an active volcano with glaciers covering just 57% of the island surface. The two largest islands are King George Island and Livingston Island, each measuring 70–80 km in length and 25–30 km in width. Their western extremities (Fildes Peninsula and Byers Peninsula, respectively) are the largest snow-free headlands in the group, measuring 10–12 km in length and 4–6 km wide. They contain numerous small lakes. Small streams are also present on many of the snow-free headlands. Smith and Elephant islands are 32 km and 45 km in length, respectively, whereas the other islands are substantially smaller, typically only 15–20 km in their longest dimension. The northern coasts abound with islets and rocks, whereas the southern coasts, which face the much deeper water of Bransfield Strait, are largely clear of such dangers. Broad beach terraces, rare elsewhere in Antarctica, are common.

The climate is Antarctic maritime. Wind directions are variable but westerlies and easterlies are about equally frequent. Skies are mainly overcast and mists, light rain, and wet snow are common. Average monthly temperatures are above freezing between December and March, whilst winter temperatures seldom fall below –25°C. During winter, the South Shetland Islands are normally entirely ice-bound. Sea ice is extensive in Bransfield Strait between July and October and it commonly extends a considerable distance north of the islands.

The South Shetland Islands contain twelve Antarctic Specially Protected Areas (ASPAs), the second-highest number for any part of Antarctica. They comprise ten terrestrial and two marine sites:

five on King George Island; one each on Nelson, Robert, and Greenwich islands; two on Livingston Island; and two on Deception Island. The ASPAs are defined on the basis of their unusually important geological and/or biological attributes. The islands also contain two sites in the process of becoming formally adopted as Antarctic Specially Managed Areas (ASMA). These are Admiralty Bay, King George Island, and Deception Island, designated due to their outstanding environmental, scientific, scenic, and historic values. There are also fourteen Antarctic Historic Sites and Monuments: five on Greenwich Island, four on King George Island, two on Elephant Island, two on Deception Island, and one on Livingston Island.

Although the South Shetland Islands are predominantly volcanic, they have a very varied geology that also includes metamorphic rocks, fossiliferous and barren sedimentary sequences, and plutonic intrusions. The different resistances of those rocks to weathering and erosion have been largely responsible for the variable physiography seen today, with mountainous terrains underlain mainly by plutonic and metamorphic rocks, and more subdued terrain associated with volcanic and sedimentary rocks.

The Elephant and Clarence Island Group and Smith Island are composed of high-pressure–low-temperature metamorphic rocks, including the first blueschists to be discovered in Antarctica. Together they form a highly deformed, mainly metasedimentary, unit 80–120 million years old in the Elephant and Clarence Islands Group, and 40–60 million years old at Smith Island. The rocks are a product of accretionary processes associated with subduction of ancient Pacific Ocean crust and associated with concurrent volcanic arc activity in the islands. A slice of oceanic crust is represented by tectonically emplaced ultramafic rock (dunite) within the metamorphic sequence on Gibbs Island.

The basement to the arc is made up of at least 3000 m of Triassic (about 240 Ma) sedimentary rock, mainly thick beds of quartzoze sandstone, which form an overturned sequence on Hurd Peninsula, Livingston Island. Deposition probably occurred in submarine fans along a continental margin, possibly within a subduction complex, although the tectonic setting is not well defined.

Marine sedimentary sequences of late Jurassic age (160–155 Ma) are exposed on Low Island. They are sparsely fossiliferous and are composed of volcanic ash derived from contemporary eruptions in the Antarctic Peninsula and deposited in a fore-arc basin. There is no evidence for volcanism located in the South Shetland Islands at that time. The main volcanic arc migrated from the Antarctic Peninsula to the islands in the earliest Cretaceous (about 140 Ma), as indicated by the highly fossiliferous marine sedimentary sequence on Byers Peninsula, which was deposited in a marine intra-arc basin and which also contains rhyolite and basalt lavas and ash deposits. These are the only rhyolites in the South Shetland group. Other Cretaceous sedimentary sequences include a striking unfossiliferous blocky deposit formed by large-scale collapse of a volcano flank (known as the Moores Peak Formation) and the Williams Point Beds, both on Livingston Island. The Williams Point Beds are volcanic sandstones and mudrocks that were deposited in a river and lake about 90 Ma. Their well-preserved fossil plants have proved to be of critical importance in understanding late Cretaceous plant evolution and radiation in high-latitude regions.

Subaerial volcanic sequences that are about 80–90 million years old (Late Cretaceous) crop out widely between eastern Livingston and northern Robert islands. They are dominated by basalt lavas. Compared to the early Cretaceous volcanism, the late Cretaceous volcanism was centred in the middle islands, indicating a trend of northeasterly volcano migration that continued into the early Cenozoic (about 60–50 Ma, the Palaeocene epoch) in western King George Island and are now found mainly on Fildes Peninsula. The geology of King George Island is the most intensively studied of all of the islands. For example, Polish geologists have identified more than twelve geological groups and thirty formations, resulting in a very complicated stratigraphy. The next major eruptions took place around 45–40 Ma, in Eocene times, from a volcano situated in central King George Island. Unlike the older volcanic sequences, the Eocene volcano was constructed of relatively evolved very thick lavas, mainly andesites, which are very well seen at Point Hennequin. The Palaeocene and Eocene sequences on King George Island also contain former lake beds with important well-preserved plant leaf fossils. They represent the most complete fossil leaf record in Antarctica.

Younger volcanic sequences are confined to eastern King George Island and continue the trend of northeasterly volcano migration previously noted. They are basaltic once again and include some of the most primitive lava compositions erupted in the islands' history. They also contain evidence for at least three major glacial periods in the geological past: the Polonez Glaciation (30–26 Ma), Melville Glaciation (23–22 Ma) and Legru Glaciation (age uncertain), and a single interglacial period (25–24 Ma). In each case, the associated ice sheets were local to the islands, although some picked up detritus derived from East Antarctica and dumped locally by far-travelled icebergs.

All of the volcanic activity was caused by subduction of Pacific Ocean crust at the South Shetland Trench. Inexplicably, despite subduction continuing to the present (although at a very slow rate today), no volcanic rocks were erupted in the South Shetland Islands between about 20 and 1 Ma. Volcanic eruptions then resumed, but were situated mainly within Bransfield Strait, where they formed volcanoes at Bridgeman, Deception, and Penguin islands and numerous submarine seamounts. Several small ash cones were also constructed on Livingston and Greenwich islands at that time. Bransfield Strait is a very young marine basin formed by stretching and rupture of the Earth's crust between the South Shetland Islands and northern Antarctic Peninsula over the past 4 million years.

The South Shetland Islands are extremely rich in breeding birds and other wildlife. There are numerous large colonies of several penguin species. They include chinstrap, gentoo, Adélie, and macaroni penguins. Chinstrap penguins are the most common and the islands contain some of the world's largest colonies for this species. By contrast, macaroni penguins are known to breed at only eight confirmed sites, although more than 14,000 breeding pairs are present. Other confirmed nesting bird species include blue-eyed shag, sheathbill, kelp gull, Cape petrel, South Polar skua, Antarctic tern, snow petrel, southern giant petrel, black-bellied storm petrel, and Wilson's storm petrel. Piles of empty limpet shells are a common sight near kelp gull nesting sites. Most of the world's population of Antarctic terns breed in the South Shetland Islands (35,000 pairs, compared with 50,000 pairs worldwide), whilst Elephant Island hosts most of the Cape petrel, black-bellied petrel, and sheathbill breeding pairs in Antarctica.

Nonbreeding species include black-browed, grey-headed, and light-mantled sooty albatrosses, which frequently visit the region and are commonly seen (in small numbers) in Bransfield Strait. Accidental migrants such as king, emperor, and rockhopper penguins are seen extremely rarely.

Marine mammals are dominated by several seal species. Fur and elephant seals are ubiquitous. Whilst fur seal populations have never recovered from depredations of the sealers in the 1820s, their numbers are now increasing steadily. From being scarce in the 1970s (when the largest concentration seen on any island was only sixty animals), they are now a common sight on many beaches, although numbers of breeding pairs are probably quite small. Weddell, crabeater, and leopard seals are also present but relatively scarce. Sei, fin, humpback, minke, and killer whales are all relatively common in Bransfield Strait, and their numbers appear to have increased significantly over the past few decades. Breaching humpbacks are a common sight off Livingston Island (South Bay). A composite fin-whale skeleton (with bones from several species) is present on a raised beach on Keller Peninsula, King George Island, and was reassembled by a team led by Jacques Cousteau in the 1970s.

The South Shetland Islands have a simple vegetation. This is generally typical of the maritime Antarctic and is dominated by over 200 lichen and 100 bryophyte (moss and liverwort) species. Two flowering plants are present: the Antarctic hairgrass *Deschampsia antarctica* and the cushion-forming pearlwort *Colobanthus quitensis*. They are the only two higher plants found in Antarctica. Both occur intermittently along the west coast of the Antarctic Peninsula (to c. 69° S), but they reach their greatest abundance and degree of ground cover at locations in the South Shetland Islands. Red and green unicellular snow algae are locally conspicuous, and there are rare occurrences of a fungi species. A striking feature is the much greater development of plant communities on the southern than on the northern coasts of the islands, with some species found only at south coast localities. The major factors affecting plant distribution and growth appear to be the degree of exposure particularly to wind, aspect (e.g., north-facing), availability of water, ground stability, and availability of nitrogen. Some plants (e.g., *Deschampsia* and the thin sheetlike green alga *Prasiola crispa*), are best developed around penguin rookeries. Elephant Island is unique in the South Shetland Islands in having a moss-derived peat bank up to 3 m deep (at Walker Point). The peat also contains remains of ash layers erupted from Deception Island over the past few thousand years, and its base has been radiocarbon-dated as approximately 5000 years old. Deception Island also contains communities of bryophytes associated with active fumarolic fissures that are unique in Antarctica.

The terrestrial fauna is also generally simple, composed primarily of microarthropods (mites and springtails) and smaller groups of soil fauna such as nematodes, tardigrades, and rotifers. The South Shetland Islands are unique in hosting populations of both higher insects found on the Antarctic continent. Both are chironomid midges (Diptera): the brachypterous (wingless) *Belgica antarctica* is endemic to Antarctica, and found from the South Shetland Islands southwards to Marguerite Bay, on the western Antarctic Peninsula; *Parochlus steinenii,* the only flying insect in the Antarctic, is found associated with water bodies on the South Shetland Islands, with a wider distribution including sub-Antarctic South Georgia and southern South America.

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See also **Adélie Penguin; Algae; Antarctic Fur Seal; Antarctic Tern; Bransfield Strait and South Shetland Islands, Geology of; Cape Petrel; *Chanticleer* Expedition (1828–1831); Chinstrap Penguin; Cormorants; Deception Island; Falkland Islands and Dependencies Aerial Survey Expeditions (FIDASE) (1955–1957); Fin Whale; Fossils, Plant; Fungi; Gentoo Penguin; Geopolitics of the Antarctic; Humpback Whale; Imperial Trans-Antarctic Expedition (1914–1917); Insects; Kelp Gull; Killer Whale; King George Island; Lichens; Liverworts; Macaroni Penguin; Minke Whale (Antarctic Minke Whale); Mosses; Nematodes; Parasitic Insects: Mites and Ticks; Protected Areas Within the Antarctic Treaty Area; Rotifers; Russian Naval (*Vostok* and *Myrnyy*) Expedition (1819–1821); Sealing, History of; Sei Whale; Sheathbills; Snow Petrel; South Polar Skua; South Shetland Islands, Discovery of; Southern Elephant Seal; Southern Giant Petrel; Springtails; Tardigrades; Volcanoes; Whaling, History of; Wilson's Storm Petrel**

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SOUTH SHETLAND ISLANDS, DISCOVERY OF

One of the most important events in the interaction of man with the Antarctic took place soon after dawn on February 19, 1819. At that time, William Smith, commander and part owner of the small merchant brig *Williams,* on passage from Buenos Aires to Valparaiso, saw "land or Ice...bearing South East by South, distance two or three leagues—Strong gales from South West with Snow or sleet..." The next day, Smith, in clearer weather, confirmed that it *was* land, noting a difficult rocky coast. Smith's landfall appears to have been off Williams Point on Livingston Island. This was the first authenticated sighting of land in the region close to the Antarctic coast.

William Smith (1790–1847), from Seaton Sluice in Northumberland, was a skilled mariner who had probably learned his craft on the east coast coal run and in Greenland whaling. By 1819, he was trading between east and west South America and had made the diversion south in order to avoid contrary winds around Cape Horn. This was unusual but, due to his Arctic experience, Smith was probably less anxious about ice than were some masters. One suspects that there was also an element of inquisitiveness about his decision.

Smith, appreciating that he was "perhaps deviating" from his insurance policy in being so far from the normal track, then resumed his voyage. On arrival in Valparaiso, he reported his discovery, plus the observation that the area had many seals and whales, to Captain W. H. Shirreff of HMS *Andromache,* the senior British naval officer on that station. Shirreff was skeptical, assuming that what Smith had seen was merely ice.

On his next voyage, which was west to east, Smith—seemingly undeterred by the insurance problem—attempted to revisit the land that he was convinced he had seen. On June 15, 1819, the wrong season for a voyage in those latitudes, Smith's progress was seriously impeded by loose ice, even though the sea was calm, and he decided to head north. On arrival in Montevideo, Smith found that the news of his discovery had preceded him, presumably overland, and the "Americans at that port" offered him money for the information. However, Smith, "having the Good of his Country at heart & as he had not taken possession of the land in the name of his Sovereign Lord the King," resisted their offers.

Smith decided on a third attempt as soon as possible. However, it took time to assemble a cargo. This had the disadvantage that in the meantime the first sealing voyages had set out for the new land. On the other hand, there was an advantage from the delay in that *Williams* was sailing at a more propitious time of year. Despite excellent weather off Cape Horn, which would have permitted an easy passage westward, Smith continued in a southerly course. This demonstrates the tenacity in his character. On October 15, 1819, Smith neared his previous position and sighted land. The precise movements of *Williams* on the next day are unclear, but it appears likely that Smith proceeded along the north of Greenwich, Robert, Nelson, and King George islands and landed by boat at North Foreland in order to take "formal possession of the land in the name of His Majesty King George the Third." Smith originally named it New South Britain but later changed it to New South Shetland on account of it lying in about the same latitude as the Shetland Islands. One source indicates that Smith, himself, did not land but sent his mate to perform the ceremony. From what is obvious in Smith's character, this seems unlikely. *Williams* then proceeded westward and on October 18, Smith sighted the island now named after him. He then bore towards Valparaiso. In the course of this third voyage, he had charted more than 200 km of new coastline. Smith arrived at Valparaiso on November 24 and reported his new findings to Shirreff, who had had second thoughts after Smith's previous report and now reconsidered the matter.

Shirreff decided to charter *Williams* with the aim of surveying Smith's new land. A one-sided contract was drawn up in which Smith accepted all the liabilities regarding the condition of the ship while the government was to pay "such amount...per month as...His Majesty's Navy shall think adequate." A party consisting of the master of *Andromache,* Edward Bransfield, three midshipmen, and a surgeon was placed on board.

Edward Bransfield (c. 1783–1852), from Cork, had been "pressed" into the Royal Navy, but became an extremely competent seaman and had rapidly risen in rank. There was an obvious potential source of friction between him and Smith because the formal relationship between them was not precisely defined. However, from the results of the expedition, one may conclude that they cooperated well.

Williams departed on December 19, 1819. Retracing her previous course, she came in sight of Livingston Island on January 16, 1820, and proceeded northeastward along the coasts of the islands noted by Smith on the previous voyage. Bransfield went ashore at King George Bay to claim the land for the King, and *Williams* put to sea from thence on January 27. They proceeded along the southern coasts of the islands, and Bransfield and the other naval personnel were heavily engaged in charting as they went. On January 29, in poor conditions, they set a southerly course, and the day after they sighted Deception Island. Later that afternoon, the weather cleared. They were "half encompassed with islands" and sighted a "high rude range (of mountains) running in a NE and SW direction" beyond them. It has been argued that this was the first sighting of a landmass on the Antarctic continent, although it is likely that a Russian expedition under Fabian von Bellingshausen had spied it several days previously.

Williams proceeded in a northeasterly direction for several days, continuous surveys being made. On January 31, they reached Hope Island, named "from the hope...that the range might continue to stretch Easterly untill joined by the Thule." They then discovered O'Brien, Seal, Gibbs, Elephant, and Clarence islands. Bransfield landed on the last for another possession ceremony. He then determined to head south in compliance with his instruction to ascertain if there was any connection with the South Sandwich Islands, discovered by Cook. *Williams* reached her farthest south, nearly 65°, on February 23, being prevented from proceeding farther by ice. She was the first vessel to penetrate what was later named the Weddell Sea.

By this time, the season was advancing, so Bransfield decided to head north. *Williams* arrived safely in Valparaiso on April 14, 1820. The expedition was a complete success because it did what it set out to do and with no loss of life.

Smith undertook a sealing voyage in *Williams* in 1820–1821 after the end of the charter. Both Smith and Bransfield continued at sea, but while the latter retired in modest prosperity, the former died in conditions of near poverty.

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See also **Bellingshausen, Fabian von; Russian Naval (*Vostok* and *Mirnyy*) Expedition (1819–1921); Sealing, History of; South Shetland Islands**

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SOUTHERN ELEPHANT SEAL

General Description

Southern elephant seal *(Mirounga leonina)* is the largest member of the pinniped family. Male southern elephant seals have been recorded to weigh up to 3700 kg. The species also exhibits the most pronounced sexual dimorphism in a mammal; females weigh 400–800 kg, which means that males can weigh 8–10 times as much as females. There are other pronounced secondary sexual differences in morphology, all of which are related to the highly polygynous mating strategy of the species. Most notable of these is the large proboscis of the male that plays a key part in dominance displays with other males.

Southern elephant seals have a circumpolar range, with breeding sites on islands scattered right around the sub-Antarctic. Very occasionally, pups are born on the Antarctic mainland.

Genetic analysis has shown that Southern elephant seals have four distinct populations; one in the southern Pacific Ocean, one in the south Atlantic, one in the southern Indian Ocean, and a small but increasing population on Peninsula Valdés in Argentina. The integrity of the populations appears to be maintained by the extremely high fidelity of animals to their natal population. Although genetically distinct, animals from the populations are indistinguishable from each other based on external features alone.

Southern elephant seals were hunted extensively throughout their range during the 1800s and early 1900s for their blubber, which yielded unusually high quality oil. This resulted in dramatic reduction in numbers at all of their major breeding sites. With the cessation of hunting, numbers increased, but since the 1950s and 1960s the populations in both the southern Indian and South Pacific oceans have declined by about 50%, although the population in the Indian Ocean appears to have stabilised since 2000. At the same time, the populations in the South Atlantic have been stable, or increasing. The underlying cause of the declines are presently unclear but are thought to be related to changes in the distribution and abundance of the seal's prey. The current estimated total population size for southern elephant seals is about 700,000.

Today elephant seals are relatively free of adverse interactions with humans. Southern elephant seals are only rarely captured in the nets of Southern Ocean fishing fleets. There are some grounds for concern that future, large-scale fisheries may compete with the seals for preferred prey species.

Life History

Elephant seals range widely from their breeding and haulout sites, and the distributions of seals from the different populations are known to overlap when they are at sea. For example, a 1-year-old seal marked at Macquarie Island was seen at Peter I Øy (68°51′ S 90°35′ W), 5200 km away in the Bellinghausen Sea, an area that is within the range of seals tracked from the Antarctic Peninsula. Most of what is now known about the movements of elephant seals comes from telemetry studies, which have radically altered our perceptions of the role of this species in the Southern Ocean ecosystem. Although elephant seals are rarely sighted in the Antarctic pack ice, we now know many adult seals spend a large proportion of their winter (post-moult) foraging trip in the pack ice and even over the Antarctic continental shelf. During this 280-day period, the seals move between 1000–3500 km from their sub-Antarctic breeding and haulout sites to foraging areas. Recent studies, which have tracked the same individuals in several years, have found the seals often return to the same feeding areas in successive years.

Female elephant seals can live, and breed, until at least 23 years of age. Females reach their maximum body size at 6–8 years but breed for the first time between 3 and 6 years. There is evidence for site-specific differences in the age at first breeding. Seals from the South Atlantic population may breed 1–2 years earlier than from the others, and this may be associated with higher growth rates in that region. Once mature, females breed most years and produce a single pup each year (although twins are occasionally born). Male elephant seals continue to grow until 10–12 years of age; the much longer period of growth enables them to reach their massive adult size.

The annual breeding cycle begins when the largest males haul out on deserted beaches in August. Pregnant females then haul out in large numbers, aggregating into harems, and giving birth to their single pup 2–5 days after arriving. The females stay with their pup throughout the ensuing lactation period, never feeding, but rather relying on their thick blubber layer to sustain them and to supply the many litres of rich, high-fat (40%) milk required by the rapidly growing pup. At birth the pups weigh between 30–40 kg, but by the time they wean at 23–25 days, pups weigh 120–130 kg.

Several days before weaning their pups, the females come into oestrus and are mated by the dominant males. Although fertilization takes place at this time, the blastocyst does not implant until several months later. This is known as delayed implantation. Once the pup is weaned, the females depart to sea, leaving the pups to fend for themselves. The pups spend the next 4–6 weeks teaching themselves to swim and hunt, during which time they rely heavily on the large reserves of blubber that they received from their mothers while suckling. When the pups eventually leave their natal beaches they spend the next 6 months at sea. This is a difficult period for the pups and as many as 30% of them die at this time.

Monacine seals, which include the elephant seals and monk seals, all have an unusual annual moult, which entails the shedding of epidermal tissue in addition to the hair. The rich supplies of blood required at the body surface for the new skin and hair requires the animals to leave the water to conserve body heat. The seals therefore spend 3–5 weeks fasting ashore in January to March, once again relying on stored blubber to supply their energy requirements.

Social Structure

Southern elephant seals are highly polygynous with large, dominant males (“beach masters” or alpha males) presiding over large aggregations of females known as harems. Males do not seriously compete for access to harems until they reach their full adult size at age 10–12. Before this time young males, although sexually mature, are not large enough to fight established males successfully, and remain at the periphery of harems trying to mate with unattended females. Competition between the males for the alpha position is intense and leads to spectacular fights. Successful males will have almost exclusive access to harems consisting of up to 100 females, and so the reproductive benefits of success are very high. Although males rarely retain beach-master status for more than 2 years, during that time they may sire over 100 pups. This has led to the evolution of the pronounced secondary sexual characteristics of immense body size and exaggerated proboscis.

Diet and Trophic Interactions

The diet of elephant seals is difficult to study because of their wide-ranging and protracted trips to sea when it is impossible to observer what they are eating. Conventional methods of diet analysis, which examine stomach contents of seals that have recently hauled out, can only provide information on what has been eaten in the few days prior to returning, and this is not likely to be representative of their diet during the entire trip. Nonetheless these types of studies have now been conducted on several age groups of seals from several populations. The general trend is for the prey to be dominated by squid, with small amounts of fish and crustaceans. There is evidence of differences in diet between males and females, and between juvenile and adult seals, but these are largely due to differences in the species of squid found, or the size of the squid taken. The dominance of squid in the diet is characteristic of all the seals that have been examined.

Recently, other techniques have been used to try to gain a more comprehensive and integrated picture of elephant seal diet. One of the most promising, although still experimental, is to use fatty acid profiles in the seals’ blubber to obtain broad-scale diet information. As prey species have characteristic fatty acid profiles, these may be incorporated in the seal’s blubber, which can then be sampled when the seal returns to shore and analyzed to give a picture of diet during its time at sea. This approach has indicated that adult female elephant seals have different fatty acid profiles between their summer and winter foraging trips, and that seals feeding in different regions also have different profiles. Seals that fed over the Antarctic Continental Shelf had fatty acid profiles consistent with a diet dominated by fish, while those feeding in regions associated with the Antarctic Polar Front had profiles consistent with diets dominated by squid.

When information on foraging location and diet are combined it is possible to estimate prey consumption rates by elephant seals in different regions of the Southern Ocean. Recent studies suggest that elephant seals are the largest consumer of squid in the pack-ice zone, particularly in the winter months.

Other Special Features

One of the most remarkable features of elephant seals is their diving behaviour. Elephant seals spend more than 90% of their time at sea submerged, feeding intensively to build up the blubber stores required to support them during the breeding and moulting haul-outs. The seals' diet of deep-water squid means that they have developed the remarkable ability to dive to depths in excess of 1900 m and for as long as 120 minutes. While these values are the extremes of those recorded, even the average values are impressive. Adult females routinely make dives of 20 minutes, and reach depths of 400–800 m. Paradoxically, although the males generally dive for longer, about 30 minutes, they do not often go as deep. This is a reflection of their tendency to feed over continental shelves, while most females tend to use deeper, oceanic water.

Another unique characteristic of elephant seal diving is the presence of "drift" dives, where the seals swim to depth of between 200–400 m, then stop and drift motionless in the water column for up to 30 minutes. The purpose of these dives is unknown, but may be associated with resting, or processing of food and metabolites that have been postponed during intensive periods of diving. What ever their purpose, drift dives offer valuable insights into other aspects of elephant seal biology because the rate of their drift has been shown to be a consequence of their buoyancy, which is in turn due to the relative amount of fat and other tissue in the seal's body. Studying drift rates can therefore provide information about changes in relative body composition throughout an individual's time at sea.

Elephant seals exhibit extremely long, deep drives. During an average dive to 500 m, a seal will experience 680 pounds of pressure per square inch (psi), or 4688 kPa. The seals avoid some physiological complications, such as the bends, by expelling almost all air from their bodies before diving, and thereby minimizing compressible air spaces. How they avoid other problems such as nitrogen narcosis and maintain cellular metabolic process at these pressures requires further research. Simple calculations based on the amounts oxygen stored in the blood and muscle of the seals and their dive durations indicate that seals must be reducing their metabolic rates while diving. For an average-sized female, dives in excess of 30 minutes would require diving metabolic rates to be less than their resting metabolic rate. Heart rates recorded on free-diving female elephant seals reflect this, declining to less than 10 beats per minute on the longest dives. An active, swimming elephant seal uses less oxygen than when sleeping on land. This is achieved through several physiological changes, such as restricting blood flow to major organs, which result in decreasing oxygen requirements.

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See also **Diving—Marine Mammals; Leopard Seal; Ross Seal; Sealing, History of; Weddell Seal; Zooplankton and Krill**

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SOUTHERN FULMAR

The southern, or Antarctic, fulmar (*Fulmarus glacialoides,* a member of the family Procellariidae, order Procellariiformes) is a broadly distributed petrel species of the Southern Ocean. It is a member of the fulmarine petrel complex, which also includes the Antarctic petrel, snow petrel, Cape petrel, northern and southern giant petrels, and the northern fulmar.

The genus *Fulmarus* contains two species, the southern and northern fulmar. The name "fulmar" likely derives from the combination of two Gaelic or Hebridean words meaning "foul gull." Presumably, this is a reference to the fulmar's habit of spitting stomach oil when threatened. Chicks are particularly adept at deterring potential predators with their stomach oil marksmanship. Of the two species, the southern fulmar is considered likely to be the more primitive, or ancient, species, with the northern fulmar presumed to have arisen from populations of southern fulmars that moved northward from the

Southern Hemisphere and were subsequently isolated by changes in global climate and oceanographic regimes.

Southern fulmars are a large petrel, ranging in body mass between 700–1000 g. Their plumage resembles that of gulls in both pattern and coloration. The underparts are white and contrast with the pale silver-gray upperparts. The wings are primarily silver-gray with a striking white rectangular patch, bordered by black outer primary feathers, on the upperwing. The bill is fleshy pink with a dark tip and lavender-blue nasal tubes. The plumage does not differ between the sexes or by age. Fulmars employ a stiff-winged soaring mode of flight interspersed with brief periods of rapid wing beats.

The species has a circumpolar distribution, occurring predominantly in the Antarctic and on some sub-Antarctic islands. Southern fulmars breed in colonies ranging in size from tens to thousands of breeding pairs. Although fulmars breed in colonies on the East Antarctic mainland and offshore islands throughout East Antarctica and along the Antarctic Peninsula, the center of their breeding distribution appears to be island groups in the Scotia Arc (e.g., the South Orkney and South Sandwich islands), based on our knowledge.

Precise estimates of the total world population do not exist, but global numbers possibly exceed 2 million birds. There are few conservation concerns for the species, given its large global population, broad geographic distribution, and generally remote and inaccessible breeding colonies. The only potential long-term threat may be interactions with commercial fisheries, although currently this does not appear to be an issue.

Breeding colonies tend to be located on cliffs or on steep slopes where birds can easily take off and land at nest sites. Southern fulmars nest on the surface, using nest sites that are simple scrapes in gravel or on flat rocks and frequently augmenting them with a few pebbles or stones. Like most petrels, southern fulmars exhibit a high degree of natal philopatry, the tendency to return to their colony of birth to establish a nest and begin to breed, and nest site tenacity, meaning that they tend to return to the same nest site to breed year after year. They are also highly monogamous, with more than 80% of breeding pairs typically maintained between seasons.

Timing of the highly synchronous breeding season shows remarkable consistency among years and regions. Birds typically begin to arrive at the colonies in October to claim and defend their nest sites and to mate. Southern fulmars, like all procellariiformes, lay a single egg. Egg laying occurs within a 10–14-day window from the first to the third week of December. Incubation of the egg, shared by both members of the pair, lasts an average of 47 days, with hatching occurring in late January. Both parents also share in the care and feeding of their chick, which remains in the nest for approximately 52 days before fledging in the second half of March. Fledglings are independent and receive no parental care once they depart the colony.

Chicks of procellariiformes typically grow much more slowly than predicted for birds of the same size. Interestingly, relative to other species in the order Procellariiformes, the fulmarine petrels (including the southern fulmar) grow considerably more quickly, nearly twice as rapidly as predicted. Their pattern of growth, however, is comparable to that of other petrels and albatrosses, with development beginning slowly but increasing throughout a linear phase before tapering off toward the end of the chick period. The breeding patterns of fulmarine petrels, characterized by highly synchronous and tightly timed breeding, a relatively compressed breeding season and rapid nestling growth, suggest that they may be an evolved response to constraints on breeding imposed by a short high-latitude season in which environmental conditions are conducive to breeding and to opportunities presented by seasonally highly abundant food sources.

The biggest survival challenge for southern fulmars is their first year of life. Mortality rates decrease significantly for birds that survive their first year. The few estimates of adult survival that exist suggest annual survival rates of 93%–95%. Age at first breeding varies but is commonly 6–8 years.

Southern fulmars forage opportunistically, which is typical of many species of petrels. Their diet is comprised primarily of fish, euphausiids (krill), and squid. Diet during the breeding season appears to vary regionally, with krill dominant in some areas and fish in others. Fulmars forage by seizing prey items from the surface and occasionally making shallow surface dives. They will also scavenge carrion when available. Although it has not yet been demonstrated for fulmars, many species of petrels are known to use olfactory as well as visual cues when foraging.

Foraging ranges are restricted during the breeding season because birds have to return to the colony to relieve their mate and/or provision their chick. Thus, breeding southern fulmars usually forage in the surrounding inshore and shelf waters within a few hundred kilometres of colonies. They feed amongst pack ice but also commonly in open water far from any ice. Foraging trips during the chick-rearing period are usually 2–4 days in length.

During the nonbreeding season, fulmars disperse out of the Southern Ocean, with most birds wintering in sub-Antarctic waters. Some individuals reach temperate waters, with some birds ranging considerably farther north and occasionally reaching the tropics along the west coast of South America.

PETER HODUM

See also **Albatrosses: Overview; Antarctic Peninsula; Antarctic Petrel; Cape Petrel; Fish: Overview; Northern Giant Petrel; Seabird Conservation; Seabird Populations and Trends; Seabirds at Sea; Snow Petrel; South Orkney Islands; South Sandwich Islands; Southern Giant Petrel; Squid; Zooplanton and Krill**

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SOUTHERN GIANT PETREL

Southern giant petrels (*Macronectes giganteus,* order Procellariiformes) are large, surface feeding predator-scavengers with a circumpolar distribution throughout the Southern Hemisphere. With a wingspan of approximately 2 m, these petrels resemble a small albatross in flight, although their build is somewhat stockier. Adult giant petrels weigh 3.5–5 kg; males are larger than females, which is the principal difference between the two genders. Known to sailors and explorers as the Nelly, Stink-pot, Glutton, Stinker, or Bone-shaker, southern giant petrels are a familiar sight within the Southern Ocean and may venture north into the lower latitudes (20°–25° S) as juveniles and nonbreeding adults. The generic name, *Macronectes,* meaning "the long swimmer," is a reference to the species' ship-following tendency and affinity for oceanic foraging.

Until 1966, giant petrels were regarded as a single species. The northern species, *Macronectes halli,* was distinguished on the basis of breeding timetables and morphology, and there is some speculation that a third, intermediate form may exist at some sub-Antarctic breeding localities. The two recognized species are reproductively isolated where they co-occur, although limited interbreeding has been documented. While the breeding distribution of northern giant petrels is limited to the sub-Antarctic islands and more northerly latitudes, southern giant petrel breeding localities span a much wider latitudinal range (45°–68° S) that includes continental Antarctica to coastal South America, suggesting they are perhaps better adapted to breed in diverse environments. Southern giant petrels are abundant at higher latitudes (e.g., on the Antarctic Peninsula), although populations can be found on all of the island groups of the Scotia Arc, on many sub-Antarctic islands, the Falkland Islands, and throughout the coastal regions of Patagonian Argentina and southern Chile. Nonbreeding adults, juveniles and fledglings range farther north than breeding adults, and tend to disperse farther than their congener, *M. halli*.

Like many other Procellariiformes that have vast oceanic feeding ranges, southern giant petrel breeding populations are also decreasing throughout much of their range. Over the past 25 years, the global southern giant petrel breeding population has decreased by approximately 18%, with current population estimates at just over 30,000 breeding pairs. Recent surveys at the Falkland islands in 2004–2005 may result in greater abundance estimates. Breeding localities in proximity to sources of chronic disturbance show the most dramatic population decreases (e.g., some sub-Antarctic islands; South Shetland Islands, Antarctic Peninsula). Despite this relatively coherent downward trend throughout much of their breeding range, some southern giant petrel breeding populations are increasing at some localities on the Antarctic Peninsula and also on the Antarctic continent. Interestingly, there have been substantial breeding population increases (approximately 50%) reported in some South American colonies during the mid-1990s.

Southern giant petrels rely on windswept landscapes to nest. Such landscapes facilitate both take-offs and landings, especially during calm conditions, and provide reliable access to snow-free nest sites to populations breeding in the higher latitudes. Nests are typically found in open areas (e.g., raised outcroppings, ridge tops, or beaches) and breeding pairs are often colonial, although colony density varies by breeding locality. Nests are often used annually by the same breeding pair and are constructed of stones, limpet shells, and moss in Antarctica, or tussock grass and other locally abundant herbaceous materials in the sub-Antarctic. Both genders partake in nest building and maintenance, and adults typically remain associated with their breeding sites during the winter

Adult male southern giant petrel feeding an 8-day old chick. Southern giant petrels brood their chicks for approximately 2–3 weeks, when the chick is most vulnerable to inclement weather and other threats. Humble Island, Antarctic Peninsula. (Photo copyright, Donna Patterson-Fraser)

while still engaged in long foraging trips away from their colonies.

Southern giant petrels are mainly monogamous, but there are well-documented cases of divorce, mate-swapping, and mate changes resulting from the disappearance of a breeding partner. A single egg is laid between late September and early November, with later timetables characteristic of Antarctic breeders. Incubation shifts are split nearly equally between both members of the pair, and incubation time is approximately 55–65 days. Chick hatching and rearing tends to be timed with maximum food abundance, in order to accommodate rapid chick development. Hatching in southern giant petrels appears to be coincident with the availability of predominant local resources (e.g., penguin carrion, krill/squid, other birds). Given the southern giant petrels' propensity for opportunistic scavenging, and a parental tendency toward gender-specific foraging, the likelihood of young chicks receiving adequate food is increased, even if one type of prey should become unavailable. Chicks fledge in 110–125 days, and fledgling dispersal patterns based on band recoveries suggest a generally eastward progression, assisted by prevailing winds, within the Southern Hemisphere. Juveniles spend the first 3–6 years at sea with occasional resightings concentrated in the Antarctic during summer and in sub-Antarctic and subtropical regions during winter. Age at first breeding is between 6 and 10 years of age, with males entering the breeding population at an earlier age than females. Interestingly, although some southern giant petrels may breed annually, approximately 30%–50% of any given population is usually on "sabbatical," meaning they may skip a year without nesting. In contrast to northern giant petrels, southern giant petrels are polymorphic, ranging in color from dark to light. A small percentage of the population (up to 15%) is represented by a nearly completely white form.

Annual reproductive success varies widely by locality, from a low estimate of 6% for some populations in the South Shetland Islands, to nearly 85% for other localities within the Antarctic Peninsula region. Common causes of reproductive failure include human disturbance, station activity and construction, overflights, starvation, trampling by a parent or neighbor, predation, and exposure during severe weather. Although records are sparse, longevity estimates are minimally 30–40 years, possibly reaching 50 years.

Southern giant petrels are both predators and scavengers. During summer, carrion (seal and penguin) is an important component of the diet. Foraging segregation between the genders occurs, with the females undertaking offshore and oceanic foraging and the males specializing in terrestrial or inshore feeding. Important prey items vary by locality and include penguins, carrion, cephalopods (squid), crustaceans (krill), fish, and other seabirds. Satellite tracking studies have revealed that foraging birds make repeated trips to the same locations where predictable food resources are available. These areas may include ice edges or polynyas, which are typically known to have higher primary production and enhanced food abundance. Southern giant petrels do not typically dive for prey but rather approach prey while sitting on the water, from which they will also feed by surface-seizing. Prey can be located by olfaction, and, although disputed, southern giant petrels may actively follow ships as part of their oceanic foraging strategies. Interactions between individuals at a food source are typically agonistic and comprise the majority of social interactions away from the nest. They have been reported attacking the corpses of drowned sailors; thus the nickname "Bone-shaker." Needless to say, southern giant petrels are effective and voracious predators, in addition to opportunistic scavengers.

Although this species is highly susceptible to some types of human disturbance near their breeding colonies, studies suggest that the observed population decreases are due primarily to mortality through entanglement in commercial longline fishing operations. These operations are rapidly expanding in the Southern Ocean, thus posing an increasing hazard to these wide-ranging predators and scavengers because they are attracted to the baited hooks associated with these fisheries. If hooked, giant petrels drown or are mortally wounded when trying to escape. Indeed, southern giant petrels are now listed as "vulnerable" by the International Union for the Conservation of Nature (IUCN), joining many other threatened and endangered populations of seabirds that are decreasing due to the massive mortality (estimated at >100,000 birds annually) associated with these Southern Ocean longline fisheries. Immature southern giant petrels are especially vulnerable because they spend several years circumnavigating the Southern Ocean in the interval between fledging and recruitment to the breeding population. The recent increase in commercial longline fishing may, in effect, become the most serious factor limiting the survival of this long-lived species.

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See also **Antarctic Peninsula; Northern Giant Petrel; Petrels: Pterodroma and Procellaria; Seabird Conservation; Seabird Populations and Trends; Seabirds at Sea; South Shetland Islands; Squid; Zooplankton and Krill**

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SOUTHERN OCEAN

The Southern Ocean and Its Early Scientific Exploration

The Southern Ocean has been described in former times as the Antarctic Ocean. Some geographers deny that there is any such thing as the Southern Ocean, believing that the Atlantic, Indian, and Pacific Oceans extend south all the way to the Antarctic continent. Others consider that the unique polar character of the surface waters south of the Polar Front, or Antarctic Convergence as it was formerly known, which lies near 50° S in the Atlantic and Indian Ocean sectors and near 60° S in the Pacific sector, define a water mass sufficiently different from those in the other three oceans to deserve its own name, and limit the Southern Ocean to that area. Yet others regard the Southern Ocean as extending all the way north to the Subtropical Convergence near 40° S, where warm subtropical surface waters meet the cooler surface waters of the Subantarctic Zone. This last definition seems reasonable from an oceanographic perspective in that the Southern Ocean so defined encompasses all surface waters influenced by oceanographic processes related to Antarctica, and incorporates the major oceanographic feature of the region, the great Antarctic Circumpolar Current, formerly called the West Wind Drift, which transports 135 million cubic metres of water per second from west to east around Antarctica. This is the world's largest current, four times as large as the Gulf Stream and 135 times the flow of all the world's rivers combined. The Antarctic Circumpolar Current is the central and dominant feature of the Southern Ocean. According to Pollard et al. (2002) it is bounded to the north by the Subantarctic Front and to the south by the southern edge of the surface outcrop of Upper Circumpolar Deep Water. The northern part of the current forms the Polar Frontal Zone; the southern part forms the Antarctic Zone, the two zones being separated by the Polar Front, identified by the northernmost extent of the 2°C subsurface temperature minimum. The different zones between the major fronts within and outside the main body of the current tend to have different water masses and different communities of plants and animals. The structure of the Current is not simple. It comprises a broad band in which the Polar Front is one of several fronts, all associated with narrow eastward current jets. South of the Current, the surface waters move to the west along the Antarctic coast, under the influence of the prevailing winds.

For centuries, the raging westerly winds, stormy seas and huge waves of the Southern Ocean deterred the hardiest of sailors from probing south. Those hardy enough to brave the winds and the waves soon had to contend with another hazard–icebergs the size of small islands. Further south yet they met another deterrent—sea ice, which in the southern winter months covers an area as large as Antarctica itself, extending north as far as 61° S on average but reaching 52° S near South Georgia. As if that were not enough, the blasting rain froze on the rigging, coating masts, yards, and ropes in thick layers of ice making ships top heavy and sails difficult to work. Just as mountain ranges and deserts prevented communication between adjacent peoples in times gone by, so the harsh and unforgiving Southern Ocean protected Antarctica from intrusion, not least by scientists.

Some believe that the great Chinese fleets of exploration in 1421–1423 were the first to sail the Southern Ocean, discovering the Straits of Magellan, visiting the Falkland Islands, the South Shetlands, and South Georgia, and sighting the northern part of the Antarctic Peninsula, as well as coming across Kerguelan and Heard Islands in the Indian Ocean, and Campbell and Auckland Islands south of New Zealand. However, conventional history credits Ferdinand Magellan with being the first to sail into Southern Ocean coastal waters, hugging the coast and reaching 53°–54° S, where in 1520 he penetrated the Strait that bears his name. Other Spanish expeditions followed the same route. In 1578, Francis Drake's ship *Golden Hind* was struck by a severe storm as he entered the Pacific Ocean from the Strait. The ship was blown south to 57° S and found indications of open water between Cape Horn and Antarctica. The existence of what became called Drake Passage was confirmed when Isaac Le Maire rounded Cape Horn in 1616. Gradually other southern lands were found, many by ships blown off course in storms, like John Davis, who discovered the Falkland Islands, at around 52° S, in 1592; Anthony de la Roche, who discovered South Georgia at around 54° S in 1675; and William Smith, who discovered the South Shetlands at around 62° S in 1819. A rich literature describes these early geographical discoveries, which set the physical framework for later ocean science.

True scientific studies of the Southern Ocean began with the second voyage of Captain James Cook in 1772–1775. Others before him had reported seeing icebergs, but Cook was the first to surmise that the tabular bergs broke away from ice sheets terminating in high cliffs extending into the sea at coasts as yet unseen. He also appears to have been the first to observe the vast fields of sea ice around Antarctica, which stopped his excursions south. Nevertheless he managed to cross the Antarctic Circle at 66.5° S three times, reaching a furthest south of 71°10′ S in the Bellingshausen Sea in January 1774. Cook's scientists measured air and sea temperatures and found that in the Antarctic region cold surface water sat on top of warmer water at a depth of 200 m. We now know that this is because the Antarctic surface water is relatively fresh from melting ice and floats atop the warmer saltier water that is spreading south below it. His main results proved that there was an ocean all the way around Antarctica, and that there must be a frozen continent to the south to produce so much ice.

Scientific studies continued with the voyage of Bellingshausen in 1819–1821, who circumnavigated Antarctica and filled the gaps left by Cook. He expanded the extent of the Southern Ocean by sailing across over 242 degrees of longitude south of 60° S, of which 41 degrees were within the Antarctic Circle. Using a tow-net he was able to show that small drifting animals (plankton) move up in the night and down in the day. In addition he made the first clear reference to the small shrimplike krill *Euphausia superba,* which dominates the zooplankton and feeds whales, seals, albatross, and penguins.

A cruise across the Drake Passage, by *HMS Chanticleer* in 1829, observed wide variation in the directions of currents, and measured current speeds of between 6 and 41 miles per day. Durmont D'Urville showed from his voyages in 1822–1825 and 1826–1829 that the temperature at great depths in the open Southern Ocean was nearly constant between 4° and 5°C. Charles Wilkes' expedition in 1839–1840 remarked on the multitudes of shrimp (i.e., krill) and concluded that they were responsible for the abundant populations of whales and penguins. The expedition led to publication of the first drawing of *Euphausia superba,* in 1855.

James Clark Ross made comprehensive studies of the Southern Ocean from the *Erebus* and *Terror* in 1839–1843, during which he discovered the Ross Sea. He was the first to make extensive soundings, which showed that abyssal depths separated Antarctic from neighbouring continents. He made many deep temperature measurements with maximum and minimum thermometers, which showed temperatures like those observed by D'Urville below 1000 m. As pointed out by Deacon (1984), the true temperature near the bottom is close to 0°C, the difference from Ross's figures being due to the effect of pressure on the early thermometers. Ross was the first to measure the motions of the tides in the region, and he deduced mean sea level at places where he stopped for long enough, as in the Falkland Islands. His scientists dredged the seabed down to 800 m and used deep-sea grabs to collect samples from deeper depths. Sadly, much of Ross's collection of fish and deep-sea animals was lost by decomposition. Nevertheless, 145 species of fish new to science were described, and Joseph Hooker's *Flora Antarctica,* published in 1858, laid the foundations for Southern Ocean botanical studies, among other things noting the importance of winds and currents in governing plankton distribution patterns.

In 1894, *HMS Challenger* made a brief excursion across the Antarctic Circle. Interpretation of the results from this and other cruises suggested that tropical water must move south to balance the effect of the cooling and dilution that goes on in the Antarctic. The cruise also led to the first overall picture of the distribution of atmospheric pressure over the Southern Ocean, finding a circumpolar ring of low pressure some 30 degrees wide in which the mean pressure falls to about 980 mb at 63° S, following which it rises towards the continent. The *Challenger's* collections of seabed rocks and sediments led to the conclusion that icebergs had carried fragments of coastal rock to the north, dropping them on the seabed as the ice melted, and showed the continental nature of Antarctica.

In 1897–1899, the *Belgica* made a rich collection of fish and bottom-dwelling animals from the continental shelf off West Antarctica and used modern deep-sea reversing thermometers to make measurements down to 4000 m that are comparable to those we would make today. They showed that water temperatures were close to –1°C at a depth of 100 m, rose to above 2°C in the warm deep layer, and fell to near 0°C near the bottom. Krill were found to be abundant in the Bellingshausen Sea.

The *Valdivia* carried out a comprehensive scientific investigation in the South Atlantic and Indian Oceans in 1898–1899, confirming the three layer structure of the Southern Ocean, with cold Antarctic surface water, warm deep water, and cold bottom water. They showed that the surface water was relatively fresh, the warm deep water quite saline, and the deep water somewhat less saline, and they identified the Weddell Sea Current, that carries cold water and ice east to Bouvetøya.

These early efforts and later complementary activities in the early part of the twentieth century, such as the first description, by the *Gauss* (1901–1903), of the sinking of cold surface waters between 40° and 60° S, and the explanation by the *Deutschland* (1911–1912) of the origin of deep cold Antarctic Bottom Water, established in outline the physical circulation and biology of the Southern Ocean. They were not surpassed until the advent of the UK's Discovery Investigations, which operated first the *Discovery,* and then *Discovery II* in the Southern Ocean between 1923 and 1951. The Discovery Investigations provided the first systematic scientific studies of whales in the region, and the ships covered the whole of the circumpolar ocean with routine measurements of temperature and salinity, and made many collections of plankton and other organisms. The result was the first detailed picture of the structure and currents of the ocean, and of the distribution of phytoplankton, zooplankton (especially krill) and whales, and other mammals in relation to ocean currents and nutrients.

Exploitation of the Living Resources of the Southern Ocean

Cook's voyage was to have an immediate and unexpected impact. He visited (and named) South Georgia, and reported on the abundance of the seals to be found there. Within 3 years English sealers were at work on the island. In 1778 they brought back from South Georgia and the Straits of Magellan 40,000 seal skins and 2800 tonnes of elephant seal oil. By the time James Weddell visited the island in 1823 the fur seals and the elephant seals were almost extinct. 1.2 million fur seals were slaughtered there between 1786 and 1825. It is no accident that South Georgia's main port was named Grytviken (meaning "pot-harbour," for the seal cooking pots). Similar slaughter followed the discovery of the South Shetland Islands by William Smith in 1819, and subsequently spread to Antarctica and all the sub-Antarctic islands. By 1829 the sealers had done their work in the South Shetlands too; the *Chanticleer* observed not a single fur seal there in 1829. Fur seals continued to be caught sporadically at a small scale through the nineteenth century. As fur seal stocks declined, the emphasis shifted to the exploitation of elephant seals for blubber oil. Exploitation was sustainable under license, and continued into the twentieth century, ending in 1964 on South Georgia. Around a quarter of a million of these animals were harvested there. The scattered knowledge on Antarctic seals was brought together by the Scientific Committee on Antarctic Research (SCAR) in 1972 and led to acceptance of the protection of fur, elephant, and Ross seals south of 60° S, and the adoption of quotas for catch limits on the crabeater, leopard, and Weddell seals under the Convention on the Conservation of Antarctic Seals (CCAS), which was finally ratified in 1978. Fur seals began recovering in about 1980 and now have a population of several million.

On many islands penguins were also harvested for skins and oil, with up to 150,000 per year being taken on Macquarie Island at the end of the nineteenth century. The impact on the penguin population does not seem to have been significant.

Mention by early explorers of the abundance of whales led inevitably to the pursuit of these creatures into the Southern Ocean. Whalers began hunting the Sperm Whale on a small scale in the northern parts of the Southern Ocean, between latitudes 30° and 50° S, almost as soon as maps of new lands there were published from the seventeenth century onwards. Sperm whaling reached a peak in 1837. Large numbers of the southern right whale were caught at the same time, before they too began to decline after the 1840s. Modern commercial whaling of the Southern Ocean south of 50° S did not begin until 1904, when harpoon guns and boats became powerful enough to hunt for the "great" whales, the rorquals like the blue, fin, and humpbacked whale. This hunting began around South Georgia, through the Compañia Argentina de Pesca, founded by the Norwegian Captain C. A. Larsen. It then grew apace, fuelled from 1926 onward by the new technology of "factory ships" that could operate independently of ports and allowed widespread exploitation of the open ocean. The industry was dominated by the UK and Norway. The harvest was not sustainable, despite regulation of the whale fisheries by bodies such as the Falkland Islands government, and, from 1946, by the International Whaling Commission (IWC). Consequently, different whale species declined one after another, with peaks in catch of the humpback whale around 1910, blue whale around 1930, sperm whale around 1953, fin whale around 1955, sei whale around 1965, and minke whale around 1975. In 1972 the UN Conference on the Human Environment called for a 10-year ban on whaling, and in 1982 the IWC declared the region to be a whale sanctuary. By 1985–1986 the IWC introduced zero catch quotas for all commercial whaling there. This ban remains in force. Whale catching came to an end at the end of the 1986–1987 season, except for limited annual catching of 300–600 of the abundant minke whales for scientific purposes by Japan. Before the whaling ban, 1.4 million whales were caught in the Southern Ocean. Recovery is slow.

The krill first observed by Bellingshausen provide the basis for a modern fishery. Much of our understanding of krill comes from the Biological Investigations of Antarctic Marine Systems and Stocks (BIOMASS), a programme of the Scientific Committee on Antarctic Research (SCAR) between 1977 and 1991. Swarms of krill may contain up to 30,000 animals per cubic metre, turning the water red or orange. Estimates suggest a standing stock of some 500 billion tonnes, of which humans could take between 80 and 150 million tonnes per year without harm to the system. The krill are found south of the Polar Front, mostly between 50° and 65° S and from the tip of the Antarctic Peninsula east to the longitude of Cape Town (20° E), with large numbers around South Georgia. Krill fishing began commercially in the early 1970s around South Georgia, the South Orkney Islands, and the South Sandwich Islands, with the catch reaching a peak of 528,000 tonnes in 1982. Since then, many of the Russian vessels doing the catching left the area, and the catch declined to

83,000 tonnes in 1998. Russia, the Ukraine and Japan are the key countries involved.

Since 1969–1970, fishing has been the most important economic activity in the Southern Ocean. It is carried out mostly around South Georgia and Kerguelen, largely for bottom-dwelling fish. The industry was started by eastern bloc countries, and is now dominated by Australia, New Zealand, South Africa, Chile, Argentina, Uruguay, and the Ukraine. Large scale harvesting of finfish began with trawl fisheries in the southwestern Atlantic sector. The main commercial species are mackerel, icefish, and Patagonian toothfish. Squid are also taken, largely around the Falkland Islands. The fishing industry is regulated by the Commission for the Conservation of Antarctic Living Marine Resources (CCAMLR), which came into force in 1982. Overexploitation has caused stocks to decline, leading to the implementation of conservation measures. In 2001 the fishing of several finfish species was banned, and the Total Allowable Catch was reduced for others. Longline fisheries were introduced in the 1980s to catch Patagonian toothfish, which sell for as much as US $6000 per tonne. As a consequence this fishery suffers from illegal and unregulated fishing. The longline fishery leads to the deaths of albatrosses and petrels, which dive for the bait when the lines are launched, and get dragged under and drowned.

The management of Antarctic Living Marine Resources by CCAMLR, and the management of environmental protection by the Antarctic Treaty mechanisms are helping to stem exploitation and to restore the ecosystem to a healthy level. These developments are all aided by scientific advice provided by the nongovernmental Scientific Committee on Antarctic Research (SCAR).

COLIN SUMMERHAYES

See also **Antarctic Fur Seal; Belgian Antarctic *(Belgica)* Expedition (1897–1899); Bellingshausen Sea, Oceanography of; Bellingshausen, Fabian von; Circumpolar Current, Antarctic; Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Convention on the Conservation of Antarctic Seals (CCAS); *Challenger* Expedition (1872–1876); *Chanticleer* Expedition (1828–1831); Cook, James; Discovery Investigations (1925–1951); Dumont D'Urville, Jules-Sébastien-César; German South Polar *(Deutschland)* Expedition (1911–1912); Hooker, Joseph Dalton; International Whaling Commission (IWC); Polar Front; Ross, James Clark; Scientific Committee on Antarctic Research (SCAR); Sealing, History of; South Georgia; South Shetland Islands; Sub-Antarctic Fur Seal; Whaling; Wilkes, Charles; Zooplankton and Krill**

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SOUTHERN OCEAN: BATHYMETRY

The Southern Ocean surrounds Antarctica south of 60° S. It is formed by three major deep ocean basins that are, in general terms, contiguous with the southern parts of the Atlantic, Pacific, and Indian oceans. It covers an area of approximately 20.3 million km^2 and reaches a maximum depth of 7290 m at the southern end of the South Sandwich Trench. Although the term "Southern Ocean" has been in common use for many years, it has only recently been defined, by international agreement under the auspices of the International Hydrographic Organisation in 2000, as the oceanic region south of 60° S. This decision delimited a fifth world ocean from the southern parts of the Atlantic, Indian, and Pacific oceans, from 60° S to the Antarctic coast. The northern boundary corresponds to the extent of interest of the Antarctic Treaty System. However, it cuts across major oceanic basins south of Africa, Australia, and the eastern Pacific Ocean. A more morphologically consistent northern limit would be about 50°–55° S and would include most of these major circum-Antarctic deep ocean basins (and abyssal plains). Therefore, the general large-scale features south of 55° S are discussed, together with a more detailed description of bathymetry south of 60° S. The more extended region, incidentally, would be close to the area of interest to Convention on the Conservation of Antarctic Marine Living Resources, based on an ecosystem approach.

The bathymetry of the Southern Ocean is the morphology or shape of the seafloor that underlies the Southern Ocean. In general terms the bathymetry of an ocean has two main components: the continental shelves that surround the continents, and have an average depth of some 500 m off Antarctica; and the deep ocean basins that are often several kilometres deep. The two are separated by steep continental slopes. The ocean basins were generally formed by the rifting of the Earth's crust at spreading centres and the formation of new oceanic crust at these spreading centres. They therefore contain morphological features that are generally related to their formation during the plate tectonic evolution of the region. These features include (1) deep ocean trenches: narrow, linear to arcuate asymmetric deeps that may reach 8000 m deep and several tens of kilometres wide; (2) broad linear ridges, also called midocean ridges, that are the spreading centres in plate tectonic evolution of the oceans; (3) fracture zones: narrow asymmetric linear ridges that extend from the spreading centres and mark the location of breaks in the oceanic crust (faults) causing offsets in the spreading centres; (4) abyssal plains: broad, deep, extremely flat regions of the older oceanic crust; (5) continental rises: gentle sloping regions between the abyssal plains and the continental shelves, where the older oceanic crust has been overlain by sediments that thicken towards, and in part are sourced from, the continents; and (6) seamounts (guyot if flat-topped): submarine volcanic edifices often associated with the spreading centres and fracture zones.

The deep seafloor of the Southern Ocean corresponds to the areas of oceanic crust surrounding Antarctica that were formed by seafloor spreading during the past 150 million years. The depth of the ocean and many of the morphological features are therefore intimately related to seafloor spreading and associated processes that took place during the breaking away (rifting) of South America, Africa, Madagascar, India, Australia, and New Zealand from Antarctica. The evolution of this oceanic crust (e.g., rifting, cooling) has given the present bathymetry of the Southern Ocean. The evolution of the Southern Ocean allowed the circum-Antarctic ocean currents to develop, which contributed to the thermal isolation of Antarctica and the formation of the major East and West Antarctic icesheets, and provided the gateway for the global deep ocean thermohaline current system to pass from the Atlantic Ocean through the southern Indian Ocean to the Pacific Ocean.

Three major oceanic basins lie around the perimeter of Antarctica at the southern ends of the Atlantic, Indian and Pacific Oceans. The deepest parts of these circum-Antarctic basins are the extremely flat areas called abyssal plains. Around Antarctica, these are the Weddell and Enderby abyssal plains that lie south of the Atlantic Ocean, the South Indian abyssal plain that lies south of the eastern Indian Ocean, and the Amundsen and Bellinghausen abyssal plains that lie south of the Pacific Ocean. These basins lie to the south of the seafloor spreading centres that caused the rifting of the continents from Gondwana and correspond in general terms to the southern oceanic crust formed at the spreading centres. As the oceanic crust cools with time after it formed at the spreading centre, its depth increases as its distance from the spreading centre increases, until the depth becomes gradually shallower again towards the continents due to the increasing amount of sediment being deposited on the ocean crust from the adjacent land mass (Antarctica). The Southern Ocean is formed generally of the southern part of these basins and the intermediate shallower areas (Kerguelen Plateau, Macquarie Ridge/Pacific–Antarctic Ridge, Antarctic Peninsula/southern Scotia Sea). A number of subbasins within the major basins or parts of these basins, particularly along the Antarctic margin, have been named as seas (e.g., Weddell Sea).

Starting at the Antarctic Peninsula and working eastwards, the main bathymetric features are as follows. The Weddell and Enderby abyssal plains stretch from about 15°–75° E, and coincide with the southern part of the Atlantic Ocean and western part of the Indian Ocean. The abyssal plains reach depths in excess of 5500 m. The Weddell abyssal plain lies in the west. The western part of this basin is the Weddell Sea. The northern margin of the abyssal plain corresponds to a complex of ridges and continental fragments forming the southern margin of the Scotia Sea in the west and with the plate boundary of the America–Antarctica ridge and the Southwest Indian ridge east of about 30° W. These latter two features form the southern boundary of the oceanic crust formed by the mid-Atlantic ridge spreading and join near Bouvetøya. Fracture zones extend from these ridges into the northern Weddell abyssal plain. The Enderby abyssal plain is east of the Weddell abyssal plain. Its northern margin of the corresponds to an offset (the Andrew Bain Fracture Zone) of the Southwest Indian Ridge in the west, and the Conrad Rise, a major seamount complex with minimum depths of less than 100 m. The major fracture zone (the Andrew Bain Fracture Zone) that offsets the Southwest Indian ridge, can be traced as the boundary between the Weddell and Enderby abyssal plain to the Antarctic coast at the Astrid ridge. The eastern margin of the Enderby abyssal plain is formed by the complex Kerguelen Plateau (a thinned continental fragment). The Valdivia abyssal plain lies between the Kerguelen

Plateau and the Antarctic continental shelf. The southern margin of the Weddell and Enderby abyssal plains comprise a number of seas separated by ridges extending north from the Antarctic continental shelf. These are—from the east—the Cooperation Sea, Cosmonaut Sea, Gunnerus Ridge, Riiser-Larsen Sea, Astrid ridge, and the Lazarev Sea. The Maud Rise (1200 m minimum depth) lies on the northern margin of the Lazarev Sea.

Kerguelen Plateau separates the Enderby abyssal plain from the South Indian abyssal plain and is itself separated from the Antarctic coast by the 3500 m deep Princess Elizabeth Trough. It is elongate in a northwest–southeast direction, is about 600 km wide, and extends for over 2000 km to the northwest from the Princess Elizabeth Trough. It rises above sea level at Îles Kerguelen and Heard Island, but most of the plateau generally lies at about 2000 m depth. At about 57° S, the Elan Bank forms a major ridge to the west for about 400 km at depths of about 2000 m. On the eastern side of the plateau, the Labuan Basin forms a 200 km wide indent into the plateau.

Kerguelen Plateau is a continental fragment, with associated igneous ocean rocks, that was detached during the early breakup history of India and Australia from Antarctica.

The South Indian abyssal plain extends from the southern end of the eastern Indian Ocean eastwards south of Australia to the Macquarie Ridge region south of New Zealand. The abyssal plain lies solely on the oceanic crust of the Antarctic plate south of the Southeast Indian Ridge, which follows close to latitude 50° S from about 100°–145° E. The deepest part of the abyssal plain (5300 m) lies between 55° and 60° S. Few seamounts of any significance have been detected there. The eastern margin of the South Indian abyssal plain, from about 135° E to the Macquarie Ridge at about 155° E, is marked by a series of north-northwest to south-southeast trending ridges and troughs corresponding to a series of fracture zones (George V Fracture Zone, Tasman Fracture Zone, and Balleny Fracture Zone) that extend from the spreading centre of the Southeast Indian Ridge to close to the Antarctic margin, and were formed during the generation of the oceanic crust of the Antarctic plate in this region. These ridges and troughs are up to 1200 km long, have a depth range of more than 1000 m, and a width of about 50 km. Just east of the southern end of the Balleny Fracture Zone lie the volcanic Balleny Islands and associated seamounts that form a linear chain of seamounts about 350 km long. Off the Antarctic continent lie the Dumont D'Urville Sea and the Davis Sea. The continental rise is relatively featureless, but a number of submarine canyons are inferred from limited bathymetric coverage.

A region of complex morphology lies south of Tasmania and New Zealand and marks the boundary between the South Indian abyssal plain south of Australia and the Amundsen abyssal plain south of the Pacific–Antarctic ridge. At the north end of this region are South Tasman Rise and the Macquarie Ridge, both features forming morphological barriers to eastwards ocean current flow. The region is marked by the major fracture zones linking the Southeast Indian Ridge to the Pacific–Antarctic Ridge as noted earlier, and a broad shallow (1450 m) region lies between the two ridges. Probably associated with the southern parts of these fracture zones are seamount chains—the Balleny Islands and seamounts noted earlier, Scott Island and associated seamounts, and several unnamed seamounts. The Adare seamounts with depths to less than 1000 m form the rift flanks of an enigmatic rift structure off northwestern Ross Sea.

The Amundsen and Bellinghausen abyssal plains lie between the West Antarctic margin and the Pacific–Antarctic ridge, a spreading centre associated with the plate tectonic development of the southern Pacific Ocean and the movement of the New Zealand region northwards away from Antarctica. The Amundsen abyssal plain lies to the west of the Bellinghausen abyssal plain. Depths are in excess of 5400 m. The Pacific–Antarctic ridge trends northeast from just north of Scott Island. It is offset to the east by two major fracture zones, the Eltanin Fracture Zone at about 54° S, and the Udintzev Fracture Zone at about 56° S. Both can be traced to the southeast for more than 1200 km from the Pacific–Antarctic ridge axis. Their cross sectional profiles are of adjacent ridges and troughs with depth range of up to 1000 m over a 50 km width. Antipodes, Pitman, Heirtzler, and Emerald fracture zones are more subdued features lying west of the Udintzev Fracture Zone towards Scott Island. At the south of the Amundsen abyssal plain, off West Antarctica at about 125° W, there is a group of seamounts—the Marie Byrd seamount and the Amundsen ridges. Existing data define seven major seamounts in the group that reach depths of less than 1000 m. Farther east, at 90° W, a 200 km long, northerly trending, ridge extends from the De Gerlache seamount. The seamount reaches less than 100 m depth. Peter I Øy lies immediately to the south, and the two may be related. The Amundsen and Bellinghausen seas lie south of the Amundsen and Bellinghausen abyssal plains, along to the continental margin of West Antarctica to the east of Ross Sea. At the eastern end of the Bellingshausen Sea (80° W) a well-developed sediment fan—the Charcot Fan—lies at the ocean end of the Charcot Canyon at the base of the continental slope. Further east, along the western margin of the Antarctic Peninsula is a series of subdued ridges oriented perpendicular to the margin and corresponding to fracture zones in the underlying oceanic crust (from the north these are the Hero, Anvers, and Tula Fracture Zones). On the upper continental rise between these fracture zones are a series of broad mounds about 700 m high, formed by contour currents on the seafloor. At the northern end of the Antarctic Peninsula margin a subdued trench (the South Shetlands Trough) occurs. The Shackleton Fracture Zone abuts the northern end of the South Shetland Islands sector of the Antarctic Peninsula margin and extends northeast across Drake Passage to South America. Drake Passage is the major ocean passage between the southern end of South America and the Antarctica Peninsula, separating the Bellinghausen abyssal plain from the Scotia Sea, the most southwestern part of the Atlantic Ocean. It is about 550 km wide and a depth of about 4000 m. It is traversed by the Shackleton Fracture Zone, a ridge that formed during the separation of South America from the Antarctica Peninsula, and has a minimum depth of about 1000 m.

The main techniques used for recording depth information measure the time for an acoustic pulse to travel from a ship to the seafloor and return. Converting the time to a depth requires an accurate knowledge of the speed of sound in seawater. Instruments have been developed that measure the travel time for acoustic pulses sent out as a fan of beams across the path of the ship, providing swath or multibeam measurements. Typically, some 120 beams or pulses are sent out over a fan about 120° in width, thus providing a swath of depth measurements over a strip of seafloor with a width about 5–6 times the depth of water below the ship. This provides highly detailed measurements, but very accurate sound velocity measurements are needed for seawater to enable the reflection (depth) points to be located accurately as well as calculate the depth precisely. Detailed bathymetric charts can be built up by running survey ship tracks parallel to each other at the swath width.

Satellite measurements of the height of the sea surface detect changes in this height that reflect the changes in the gravity over the sea surface, caused to a large degree by changes in bathymetry. These height changes can be used to calculate the changes in gravity under the satellite, which in turn can be used to calculate the changes in water depth. As satellite coverage is global in extent, these data can be used to provide estimates of depths where no ship-based data exist. A global digital bathymetric map incorporating satellite coverage to 70° S has been produced by Smith and Sandwell. Unfortunately, for the Antarctic region, calculations of this sort are not possible where sea ice exists, and significant gaps in information exist in some coastal regions.

Antarctic bathymetric datasets are lodged in the United States at the National Geophysical Data Centre (NGDC) at Boulder, Colorado. NGDC also operates a worldwide digital databank of oceanic soundings on behalf of the member countries of the International Hydrographic Organisation. The national Antarctic data centres (NADC) of the Antarctic Treaty System hold metadata of research databases—accessed through the Antarctic Data Directory of the Scientific Committee for Antarctic Research (SCAR). Data sets also exist at several research institutions. Multibeam bathymetric data are being managed by Lamont Doherty Earth Observatory of Columbia University.

Antarctic bathymetric charts and gridded data sets have been compiled by several organizations, and detailed bathymetric compilations have been produced by research groups working in the Southern Ocean. The General Bathymetric Chart of the Oceans (GEBCO) maps compiled in 1981 have been published. The NGDC have compiled the ETOPO2 gridded global database, using ship-based bathymetric data and the Smith/Sandwell models. GEBCO has updated its database as a gridded database, which includes a new compilation of the Indian–Australian sector of Antarctica. A new compilation, the International Bathymetric Chart of the Southern Ocean, was started in 2004 under the auspices of SCAR and GEBCO.

Fred Davey

See also **Antarctic: Definitions and Boundaries; Antarctic Treaty System; Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Continental Shelves and Slopes; Gondwana; Plate Tectonics; Sediments and Paleoceanography of the Southern Ocean; Thermohaline and Wind-Driven Circulations in the Southern Ocean**

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SOUTHERN OCEAN: BIOGEOCHEMISTRY

Biogeochemistry as a scientific field recognizes the dominant influence of organisms and ecosystem processes on the cycling of elements in the planetary system. The Southern Ocean surrounding Antarctica is one of the largest contiguous biomes on the planet and exerts powerful controls on the ocean carbon and silicon cycles, and on the exchange of carbon dioxide (CO_2) between the ocean and atmosphere. The Southern Ocean below 50° S, with 10% of the total ocean area, is responsible for ~20% of the global ocean CO_2 uptake and 50% of sedimentary opal accumulation. Here the focus is on the roles played by the open Southern Ocean and the Antarctic marginal ice zone and coastal regions in these elemental cycles as well as on some of the ecological processes influencing the cycles.

CO_2 Exchange

The exchange of carbon dioxide across the air-water interface is influenced by the gradient in partial pressure of dissolved CO_2 gas (pCO_2) between the atmosphere and the ocean water, termed the ΔpCO_2. Atmospheric pCO_2 is about 380 ppm, and the pCO_2 in seawater varies between about 200 and 500 ppm although the range in some coastal areas can be larger. When seawater pCO_2 is below 380 ppm, CO_2 is driven into the water; when it is greater, CO_2 degasses from the ocean into the air. When the gradient is large, the gas flux is faster. The ocean in the past century became a net sink for atmospheric CO_2 because anthropogenic emissions have elevated the atmospheric pCO_2 by about 30% above its preindustrial level of 280 ppm. The ocean is now responding to this relatively rapid change in atmospheric chemistry, but the time to establish a new air-sea equilibrium (assuming anthropogenic emissions are eventually stabilized) is poorly known and will take centuries to millennia. Gas exchange is also directly proportional to turbulent mixing caused by wind shear. Faster winds increase the exchange rapidly as the cube of the wind velocity.

The Southern Ocean is responsible for ~20% of the global ocean CO_2 uptake (0.47 of 2.2 Pg C yr^{-1}; Takahashi et al. 2002; 1 petagram Pg = 10^{15} g). Polar continental shelves covered by seasonal sea ice have been hypothesized to act as rectified (one-way) CO_2 pumps, due to the phasing of sea ice cover and biological activity. In summer, when primary production is high and pCO_2 is low, Antarctic seas act as strong sinks for atmospheric CO_2. In winter, when respiration dominates over production and pCO_2 is high, gas exchange is prevented by the sea ice capping the ocean surface. Sea surface temperature is almost constant near Antarctica (relative to lower-latitude systems), and the CO_2 partial pressure excursion governing gas exchange is almost entirely due to biological drawdown and respiration. The Ross Sea polynya may function as a rectified sink for atmospheric CO_2 because it is strongly undersaturated in CO_2 in summer in response to the *Phaeocystis* bloom (Takahashi et al. 2002) and covered by ice during the rest of the year.

Whether the continental shelves of other areas such as the Antarctic Peninsula act as rectified or even unrectified net annual CO_2 sinks is not established. The Peninsular region is characterized by large spatial and temporal variability and by the co-occurrence of various biological (e.g., respiration and photosynthesis) and physical (e.g., heating, cooling, ice formation and ablation, freshening, and dilution) processes, all of which makes understanding and budgeting the carbon cycle very challenging. In summer (January), different regions of the Peninsula showed different patterns of CO_2 and O_2 (dissolved oxygen) over- and undersaturation, resulting from spatial variation in dominance of various physical or biological processes. Dissolved CO_2 was near atmospheric equilibrium in some regions, particularly offshore and toward the north. Net primary production is the dominant process in the inshore areas and especially in Marguerite Bay, leading to strong drawdown of DIC (dissolved inorganic carbon) and undersaturation of dissolved CO_2 ($pCO_2 < 200$ ppm). Other areas had excess CO_2 as a result of strong respiration.

The interior shelves and coastal regions of the Antarctic are small, however, and their influence on the global CO_2 exchange is slight. The regional fluxes are dominated by the larger areas of the Southern Ocean surface further away from the continent. The outer areas of the marginal ice zones 60°–70° S seem to exhibit low net CO_2 uptake from the air. In the permanently open areas of the Southern Ocean beyond the northern extent of the annual sea ice, CO_2

exchange occurs year-round but the pCO_2 excursions are less dramatic than in the coastal areas. The region between 50°–60° S is a net sink for CO_2 with fluxes of 1–2 moles CO_2 m^{-2} y^{-1}. These are moderate to low fluxes, but the area is vast, and the region serves as an important zone of CO_2 storage on the global scale.

Carbon Cycle

Air-sea gas exchange itself is strictly a physical-chemical process governed by gas solubility as it is influenced by temperature, salinity, alkalinity, partial gas pressure, and wind. However the amount of CO_2 dissolved in the water is also influenced profoundly by biological processes that produce and consume this important biogenic gas. Biological, chemical, and physical processes are linked through the action of the Solubility Pump and Biological Carbon Pumps (Volk and Hoffert 1985; Ducklow et al. 2001). CO_2 solubility is a function of temperature: more CO_2 dissolves in cold water than warm. The Solubility Pump transports dissolved inorganic carbon (DIC or TCO_2) against the vertical concentration gradient toward long-term storage in the deep ocean as cold waters with high CO_2 concentrations sink to depth (Feely et al. 2001).

The Biological Pump is responsible for vertical sedimentation of particulate and dissolved organic matter from the illuminated (euphotic) zone in the upper 100–200 m. The components of the biological pump are plankton organisms: autotrophic phytoplankton, bacteria, protozoans and larger zooplankton, and the trophic (feeding) interactions linking these groups in the foodweb. Phytoplankton fix inorganic nutrients into organic matter, a fraction of which is exported passively through gravitational sedimentation of organic matter and actively by zooplankton migration. The biological pump operates most efficiently when blooms of larger phytoplankton like diatoms sink without being grazed upon. Zooplankton like krill and salps repackage phytoplankton and other small particles into larger, rapidly sinking fecal pellets and marine snow. Primary production in the Southern Ocean, especially in the marginal ice zone is dominated by diatom blooms, and as a consequence particles sink rapidly in conspicuous pulses. The zooplankton community alternates over interannual scales between dominance by krill and salps which influence export in contrasting ways. Krill may decrease flux, even while producing rapidly sinking particles, by reingesting them as they sink. Salps vacuum the water column of a wide range of particle sizes and produce very rapidly sinking aggregates which themselves scavenge particles and grow as they sink. Krill versus salp dominance seems to be related to watermass variations and ENSO (El Nino Southern Oscillation); thus climate change may affect the biological pump (Loeb et al. 1997).

Sedimentation has been monitored throughout the annual cycle and over several years using sediment traps deployed in the Ross and Weddell Seas and off the Antarctic Peninsula. Sedimentation on the mid-continental shelf of the Antarctic Peninsula near 64° S ranges between 1%–10% of the annual primary production (1%–10% efficiency) with an annual flux of 0.5–4 gC m^{-2} y^{-1} and peak short term rates of 40–80 mgC m^{-2} d^{-1}. Particle flux exhibits extreme seasonality with a strong peak in the summer following the ice retreat and phytoplankton bloom when more than half the total flux may occur. In the Austral winter flux is generally negligible. The summertime peak includes both the remnant sea ice community, mostly pennate diatoms, as well as water column forms. The timing of the annual sedimentation episode is remarkably consistent, but the duration, amplitude, and total size (integrated flux) all exhibit significant interannual variability. In particular the annual sedimentation varied by nearly an order of magnitude over an 11-year observation period. In the Ross Sea sedimentation ranged from 2–14 gC m^{-2} y^{-1} with a strong north-south gradient from 73°–76° S (Collier et al. 2000). The peak flux occurs later than in the Peninsula with highest fluxes in March–April. Export efficiency as measured by sediment traps is quite low in both regions, indicating that much of the production is consumed and recycled in the upper 200 m.

Export efficiency is likely low because primary production is limited by iron availability over most of the Southern Ocean which is generally remote from continental sources of windborne dust. Iron limitation is seasonal in coastal regions and marginal ice zones and more persistent over the open sea.

Biogenic production can be in dissolved as well as particulate forms. A major difference between lower latitude and Antarctic polar ecosystems is the partitioning of organic carbon production and export between these two forms. In the subtropics dissolved organic carbon (DOC) may constitute up to half the export, with strong seasonal variation. However, the net production and subsequent export of DOC in higher southern latitudes appears to be negligible. In the Sargasso Sea, about 70% of the annual production flows through the dissolved phase, whereas in the Ross Sea about 70%–80% of the production remains in particulate form and sinks or is respired back to CO_2. The reasons for this global-scale contrast are not clearly understood, but they have important consequences for carbon storage in the deep sea.

Rapidly sinking particles are transported to greater depth before they are respired back to CO_2 than dissolved organic carbon, which depends on the slow mixing and sinking of water for downward transport. Thus organic carbon transport and storage is generally deeper in the Southern Ocean than in the subtropics.

Silicon Cycle

Diatoms are large phytoplankton (c. 20–200 μm long). They are the dominant primary producers in Antarctic waters and require silicon for growth. They have dense, ornamented opal plates or frustules covering their cells that serve as a deterrent to predation and, after the cell dies or loses buoyancy, enhance sinking rates. Thus besides their role as primary producers, diatoms are important vectors for export from the upper ocean. Silicon exists in seawater in dissolved form as silicate, Si(OH)4. The highest surface concentrations in the world ocean, 30–70 μM, are found in the Southern Ocean below the Antarctic Polar Front Zone (~60° S). These high concentrations, resulting from deep mixing, support the high diatom productivity. As a consequence of high production and rapid sinking rates, the sediments underlying the Southern Ocean are highly siliceous (>5% opal by weight) and account for about 50% of opal accumulation in the world ocean.

Silicate deposition (silicification) by diatoms is an active physiological process closely tied to cell wall synthesis and regulated by ambient nitrogen to iron concentration ratios in addition to silicate concentrations. When diatoms are iron-replete, cellular Si:N ratios are about 1 but can be much greater (~10) when iron is limiting, as it usually is in the Southern Ocean. This effect further enhances silica deposition in Antarctic waters. The opal cell wall is not a simple mineral covering, which would dissolve readily, but is instead deposited within an organic proteinaceous matrix maintained by the cell. Healthy active diatoms maintain neutral buoyancy by producing lipids, but buoyancy is lost when the cells die. As they sink, the protein matrix protecting the opal cell wall is attacked by bacteria through extracellular proteases (Bidle et al. 2002), exposing the opal to physical dissolution. The rates of proteolysis are a function of temperature, and are about three times faster at 20°C than at 2°C. In low latitude waters where surface temperatures are 10°C–30°C in the upper 500 m, diatoms rapidly lose their organic matrices, and opal dissolves before they sink into colder deep water. In the cold Southern Ocean the bacteria-enhanced decomposition and dissolution of the opal is inhibited, and the opal is preserved. Diatom dissolution and silicate remineralization was once believed to be a strictly chemical process but is now understood to be under strong biological as well as temperature control. This effect may explain the vast siliceous plains of sediment below the Southern Ocean.

Like other nutrients such as N and P, Si is stripped from surface ocean waters by biological uptake and sedimentation. If the organically bound silica were not remineralized back to silicate and returned to the surface by mixing and upwelling, diatom production would cease as the silica was depleted. Some fraction of the bound silica is regenerated *in situ* by bacteria and zooplankton, but most occurs in the midwater column between 100–500 m. The silica in this layer is returned to the surface, but not necessarily in the same geographic locations where it was originally fixed by diatoms and sank to depth. Diatom silicate produced in the Southern Ocean and regenerated in deeper water is transported horizontally in Subantarctic Mode Water (SAMW) far from its origin. SAMW sinks in the Subantarctic Zone and Antarctic Polar Front region and then flows north, spreading throughout the world ocean, returning to the surface in the upwelling regions of the eastern Pacific off South America and in the North Atlantic. In this way silica originally fixed by diatoms in the Antarctic is returned to surface waters to support diatom production globally. Computer simulation experiments suggest that silica in SAMW may support 75% of the diatom production north of 30° S latitude throughout the world ocean (Sarmiento et al. 2004).

Climate Change

The critical involvement of biological processes controlling geochemical cycles suggest that Southern Ocean element cycling may change greatly—though in still unexpected ways as climate warms in the next decades and centuries. Primary production, organic matter sedimentation, and silica cycling and deposition are all active biological processes under control by temperature and associated with the cycle and extent and duration of sea ice cover. As the Southern Ocean warms and sea ice declines, these processes will be altered, but it is not certain if they will increase or decrease. Primary production and sedimentation may decline if sea ice extent is the dominant control but could increase as more ocean area is exposed to solar irradiance. Ocean warming may enhance silica dissolution and retard the large-scale transport of Antarctic silica to remote regions, inhibiting primary production globally but increasing it locally. Biogeochemistry illustrates the important interplay of physical, chemical, physiological, and ecological processes governing the current, past and future state of the Earth System.

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See also **Biodiversity, Marine; Carbon Cycle; Chemical Oceanography of the Southern Ocean; Climate Change Biology; Earth System, Antarctica as Part of; Ecosystem Functioning; Food Web, Marine; Mineralization; Phytoplankton; Polar Front; Productivity and Biomass; Zooplankton and Krill**

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SOUTHERN OCEAN CIRCULATION: MODELING

A fundamental problem in physical oceanography is determining the evolution of the state of the ocean over time. To do so, we have to solve equations for the ocean's momentum (mass times velocity) and its equation of state (essentially its density, a function of temperature, salinity, and pressure), and account for the constraint imposed by mass conservation. Those equations are complex, but numerical models with suitable boundary conditions have been widely used to simulate the circulation of the Southern Ocean. These models solve the pertinent equations on a discrete grid across time and space. For coarse resolution models, the horizontal grid spacing is typically 100–500 km, while high-resolution models have a grid spacing of 10–50 km or less. High-resolution models provide a more detailed description of the processes, but require much more computer time to perform a simulation. It is thus difficult to model the circulation at high resolution over long periods or large areas or to test hypotheses requiring a large number of simulations. Coarse and high-resolution models are thus complementary tools, the choice between them depending on the problem studied.

Models may cover domains ranging from a particular basin or region, in which case they can be at a relatively high resolution, to the entire Southern Ocean. In addition, the Southern Ocean provides the only deep connection between the Atlantic, Pacific, and Indian oceans; indeed, some of the Earth's major water masses acquire their characteristics in the Antarctic region before invading the other oceanic basins. It is therefore crucial to correctly reproduce the characteristics of this region in global models, which are widely used to analyze the Southern Ocean circulation, its global influence, and its response to remote changes.

Models must also take into account the influence of processes that occur at small scales, such as the turbulence that is responsible for vertical mixing near the sea surface. This usually involves parameterization of those processes (representation of physical effects in a model by simplified parameters), based on the dynamic equations and empirical evidence. High resolution models are able to simulate or permit the development and evolution of mesoscale eddies, swirling horizontal structures that are generally smaller than 100 km, whereas the influence of such eddies must be parameterized in coarse resolution models. This is particularly important for the Southern Ocean, where eddies play a large role in meridional (north–south) exchanges and in maintaining the vertical structure. Another difficulty of Southern Ocean modeling is the intrinsic coupling between ocean circulation and the sea-ice cover, which has a paramount influence at high latitudes on heat, salt and freshwater fluxes, as well as on stress exerted at the ocean surface. As a consequence, Southern Ocean models are generally coupled to a sea ice model and driven by atmospheric conditions derived from observations or "reanalysis" products generated by weather forecast centers. The quality of those products is lower in the Southern Ocean than in other regions due to data scarcity. Alternatively, ice-ocean models coupled to atmospheric models can be affected by problematical boundary conditions at the ocean surface, a large source of uncertainty in Southern Ocean modeling.

Despite those difficulties, models can reasonably simulate general characteristics of the ocean circulation, as well as the large-scale water mass properties. Comparison between the observed and simulated tracer evolution, in particular of the chlorofluorocarbons which provide relatively straightforward information about ocean "ventilation," has proven to be valuable in assessing model performance. Coarse resolution models are unable to precisely reproduce the details of circulation on the continental shelves or exchanges between the continental shelves and the deep ocean. Higher resolution models appear to be more capable in that domain, allowing a quantitative comparison between the characteristics of observed and simulated water masses. Such models have also been used to analyze processes responsible for the formation of water masses on the continental shelves, including exchanges between the ocean and ice shelves and the role of tidal mixing. In some regions of the Southern Ocean, the models experience difficulty simulating vertical mixing and the weak vertical stratification below the surface mixed layer. This stratification results from a delicate balance between horizontal and vertical processes and appears to be very sensitive in some models to the surface freshwater flux. Uncertainty in that quantity could strongly impact the stratification, the vertical heat flux, the ice cover simulated by the model, and the properties and formation of deep waters.

Models have been used to examine the formation processes of Antarctic Intermediate Water and Antarctic Bottom Water, two of the major water masses in the global ocean. For example, the production and properties of bottom water are strongly influenced by the large amount of brine released during sea ice formation on the Antarctic continental shelf. As the waters there are generally maintained at temperatures close to the freezing point, added salt can increase their density enough to enhance mixing and sinking along the continental slope. Shelf waters thereby become one of the major constituents of bottom water. On the other hand, net sea ice melt and higher precipitation at slightly lower latitudes tends to stabilize the water column and may contribute to the low salinity signal characteristic of intermediate water.

A dominant characteristic of the Southern Ocean is the absence of any continental barrier between 56° and 62° S, at the Drake Passage between South America and the Antarctic Peninsula. This allows the existence of a strongly zonal (west to east) Antarctic Circumpolar Current. Models have shown that the transport of this current through the Drake Passage is set by the strengths of the wind-induced near-surface northward oceanic transport and the deep northward export of dense water formed close to Antarctica. These transports are partly compensated by a southward flow of intermediate water, between roughly 200 and 2500 m, which is diverted eastward by the Coriolis force, contributing to a stronger circumpolar current.

Model results have indicated that the wind-driven upwelling of intermediate and deep water at Drake Passage latitudes could control deep water production in the North Atlantic, where that process has a large impact on ocean heat transport and climate. This hypothesis requires that Southern Ocean upwelling be the only sink for deep water produced in the North Atlantic. Any change in wind stress and upwelling in the Southern Ocean would influence deep water production in the North Atlantic, the source and sink being necessarily equal at equilibrium. More recent model results have suggested that this "Drake Passage effect" is relatively weak because of other deep water sinks. This does not mean that the role of the Drake Passage in the oceanic circulation is only restricted to its direct impact on the circumpolar current. For example, if the Drake Passage is closed in a model, then a strong warming occurs south of 60° S due to increased southward ocean heat transport. This warming is associated with a reduced sea ice cover, an increase in deep water formation close to Antarctica, and a decrease in deep water formation in the North Atlantic.

In addition to modeling of the time-averaged circulation, it is also possible to model processes responsible for temporal variability of the Southern Ocean. Most studies devoted to that subject have focused on surface variability in relation to the sea ice cover, probably due to the larger applicable data inventory. When driven by appropriate forcing, such models can simulate the dominant characteristics of the major modes of atmospheric variability, allowing analysis and description of the Southern Ocean response. Variability below the surface layer has also been described in models, and the responsible mechanisms analyzed, but the scarcity of subsurface data makes it difficult to assess the reality of the modeled features.

In the examples presented above, data are used a posteriori in order to test model skill and suggest model improvements. It is also possible to combine observational data and dynamical principles using techniques such as data assimilation and inverse methods. The goal is to profit from available observational information and ocean physics to derive essential parameters that cannot easily be measured, such as vertical diffusivity and viscosity. In inverse box models (e.g., the ocean is divided into boxes whose boundaries are defined by vertical sections of ocean data and continental barriers). In the Southern Ocean, meridional sections south of Africa, Australia and South America, and zonal sections at various latitudes are often used. Within the boxes, conservation of mass and some tracers are assumed for specific layers in order to obtain a set of equations that account for vertical exchange between the layers. The tracers can be temperature, salinity, or biogeochemical parameters, but conservation will not apply in the top layer for some variables because of air-sea fluxes. The oceanographic data provide the tracer values at lateral interfaces between the boxes that are used to compute the fluxes. The data also provide a dynamic constraint on the unknown velocity at those interfaces, using the "thermal wind" equation, which states that the horizontal gradient of density is proportional to the vertical gradient of geostrophic velocity (a flow where the Coriolis and horizontal pressure forces are balanced). Information about wind stress is then applied to estimate transport in the surface layer. This method often provides an "underconstrained" system, from which one of several solutions must be selected. Nonetheless, this method provides an estimate of the flow across key ocean sections, along with the heat and salt transport, the production and the conversion of water masses between layers, and the error bars on those values. Such estimates are instructive as they are consistent, within defined bounds of uncertainty, with both the ocean physics and observations.

HUGUES GOOSSE

See also **Antarctic Bottom Water; Antarctic Intermediate Water; Circumpolar Current, Antarctic; Climate Modelling; Coastal Ocean Currents; Ice–Atmosphere Interaction and Near-Surface Processes; Sea Ice, Weather, and Climate; Southern Ocean: Climate Change and Variability; Southern Ocean: Vertical Structure; Thermohaline and Wind-Driven Circulations in the Southern Ocean**

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SOUTHERN OCEAN: CLIMATE CHANGE AND VARIABILITY

The Southern Ocean surrounding Antarctica, the coldest, driest, windiest, and highest continent in the world, is the only ocean in the world with currents that circle the entire globe, thus transporting and mixing climate signals from one oceanic basin to another. Extremely cold temperatures and excessive salt content from the process of sea ice formation in winter produce the densest sea water on the continental shelf along coastal regions of Antarctica, which is the source of the densest water on the bottom of global oceans. In contrast to the Arctic Ocean, seasonal sea ice around the periphery of Antarctica can freely grow and extend northward under the influence of seasonal atmospheric and oceanic forcing without the restriction of landmasses. The atmospheric variability above the surface is not only influenced by the regional geography (e.g., land-ocean distribution in the Southern Ocean) but is also closely connected with climate variability in the tropics. Therefore, the three components of the climate system in the Southern Ocean, atmosphere, ocean, and sea ice, exhibit a high degree of covariability regionally and a high degree of connectivity with the rest of the world. These climatic characteristics have been documented in modern instrumental records.

The most important feature of the Southern Ocean is the Antarctic Circumpolar Current (ACC), which flows within the circumpolar belt around Antarctica and provides the deep ocean link among the major ocean basins. The ACC transports water from west to east at a rate of well over 100 Sv along a 21,000 km path, propagating and mixing climate anomalies along its way. Because of the connectivity of the Southern Ocean, the ACC becomes a key component of global thermohaline circulation, allowing oceanic route telecommunication of climate anomalies to remote regions in both hemispheres at a variety of time scales. The thermohaline circulation linked with the ACC, consequently the meridional transport of climate signals, occur at different depths of the Southern Ocean.

At surface and mid-depth of the ocean, the ACC acts as a barrier, limiting poleward heat transport and forcing an everlasting glacial state of Antarctica. Near the ACC, the northwards Ekman transport forces low salinity surface water sliding into subsurface layers in midlatitudes, forming the Antarctic Intermediate Water and Subantarctic Mode water north of the ACC. These waters spread at mid-depth of the subtropical gyres, transporting fresher water northward and playing a major role in the uptake of atmospheric CO_2. They are also mixed with the surface water above, influencing sea surface temperature in regions away from their formation sites at decadal time scales. Below them is the North Atlantic Deep Water, which is formed near the Labrador Sea and Greenland Sea, flows to the South Atlantic and then spreads over other ocean basins via the ACC. The Subantarctic Mode Water and Antarctic Intermediate Water also plays an important role in recycling the North Atlantic Deep Water and closing the thermohaline circulation.

At many sites along the continental margins of Antarctica, intensive cooling and salt ejection from sea ice formation in austral winter produces the coldest and densest water that sinks to the bottom of the ocean along the continental slope, forming the Antarctic Bottom Water. This water floods the deepest part of the global ocean. Changes in polar climate in complex interaction with sea ice and glacial ice would be carried away a great distance with the spread of the bottom water. Sinking of the Antarctic Bottom Water in high latitudes and Antarctic Intermediate Water in midlatitudes balances the upwelling of Circumpolar Deep Water in between, which results from the mixing of the penetrating North Atlantic Deep Water with surrounding waters. That completes the thermohaline circulation in the Southern Ocean.

Therefore, the vertical thermohaline structure in the Antarctic Zone, the region south of the ACC, consists of relatively fresh and cold surface water above the warmer but saltier Circumpolar Deep Water, on top of the densest Antarctic Bottom. This region is influenced under seasonal sea ice cover, which is intricately involved with water mass modification processes. In addition, the Circumpolar Deep Water provides a tremendous heat resource that can be released to the atmosphere under the condition of deep convection. That potentially can impact regional climate or even global climate. The Weddell polynya in the mid-1970s is such a deep convection event. (The Weddell polynya is a large open water area [about 350,000 km^2] within the ice covered Weddell Sea during the austral winters of 1974–1996, within which the ocean stratification was destroyed by vigorous deep reaching convection.) The heat storage in the upper Circumpolar Deep Water was vented to the atmosphere. Even though the quantitive climatic impact of such an event is uncertain, abrupt temperature cooling was observed to nearly 3000 m depth and significant changes in air-sea heat flux were found.

A unique feature of Southern Ocean climate variability is a number of clearly identifiable climate patterns in the atmosphere that are generated by different physical and dynamical processes. First, the Southern Annular Mode is marked by quasi-zonally symmetric but out-of-phase pressure anomalies between mid- and high latitudes. The Southern Annular Mode is a counterpart of the Northern Annular Mode in the northern hemisphere. The positive phase of the Southern Annular Mode represents a pattern of below-normal pressure on the Antarctic Continent and above-normal pressure in southern midlatitudes. This donut-shaped pressure anomaly pattern dominates variability of the pressure field in the Southern Hemisphere with maximum variability at 10 days period and explains over 50% of the sea level pressure monthly mean variance over Antarctica. The mechanism that maintains this climate mode is suggested by a positive feedback between eddy activity in mid-high latitudes and zonal mean flow. The Southern Annular Mode has experienced a significantly increasing trend toward its positive phase over the last 50 years. This increasing trend indicates a stronger westerly over the subpolar Southern Ocean, consequently enhancing meridional overturning in the ocean through the changes of Ekman transport as suggested by modeling studies. In addition, long-term annual and seasonal mean changes in extratropical cyclone frequencies in the southern hemisphere are also in line with the increasing trend of the Southern Annular Mode. Reduced occurrences of cyclones over higher latitudes and increased occurrences of cyclones in midlatitudes in the Southern Ocean are observed during 1958–1997. Numerical modeling suggests that this positive trend in the Southern Annular Mode will likely continue through the twenty-first century as global warming proceeds.

The Semi-Annual Oscillation is another quasi-zonally symmetric mode in the southern extratropics.

It consists of the twice-yearly contraction and expansion of the pressure trough around Antarctica, in response to differences in heat storage between Antarctica and midlatitude oceans. Thus the Semi-Annual Oscillation is characterized by the twice-yearly enhancement in meridional gradients of temperature and pressure fields. In response to the variation in the pressure gradient, the westerlies show equinoctial maxima that are 20%–30% stronger than those in summer and winter. The atmospheric convergence line with a strong half-year cycle exerts significant influences on the seasonal asymmetric behavior of ice extent: slowly advancing equatorward in fall and fast retreating in spring. In the western Antarctic Peninsula, the timing of the semiannual migration of the Circumpolar Trough dynamically influences the timing of sea ice advance and retreat. Moreover, in conjunction with pressure rises over Australia, Africa, and South America the expansion of the low pressure belt in autumn causes an amplification of the wavenumber 3 structure in midlatitudes of the Southern Ocean. This enhances meridional circulation and directly influences air transport from lower latitudes toward the Antarctic Continent, consequently causing the reduction of seasonal cooling on the continent. Even though the direct mechanism generating the Semi-Annual Oscillation is the seasonal solar heating and differential heat storages between mid- and high latitudes, the variation of the Semi-Annual Oscillation is not limited at seasonal time scale. It exhibits variability from synoptic to interannual and longer time scales due to modification by and interaction with other climate patterns. An observed change in the Semi-Annual Oscillation is the dramatic weakening of its amplitude since the mid-1970s. Studies have linked this change to the decrease of meridional air exchange that causes the cooling trend in coastal east Antarctica.

Another distinct climate pattern is the quasi-stationary wavenumber 3 pattern in midlatitudes of the Southern Ocean, a predominant winter mode in pressure/wind fields. The land/ocean distribution in midlatitudes is suggested that creates and maintains the wavenumber 3 pattern. Research showed that three southerly branches of the wavenumber 3 pattern coincide with three northward maximum extent of sea ice edge during late winter 1996, indicating the role of the wavenumber 3 pattern in advancing the ice edge. The wavenumber 3 pattern is also positively coupled with the ice edge distribution, promoting eastward propagation of the ice edge maxima and providing preferred locations for cyclonegenesis in the open ocean north of the ice cover. The long term variability of this climate pattern has not been thoroughly studied yet.

The Pacific South America pattern, which dominates climate variability in the subpolar South Pacific, is also a distinct climate mode in the Southern Ocean. It consists of three anomalous pressure centers with alternating phases in east of New Zealand, Amundsen /Bellingshausen Seas, and over South America/the South Atlantic. This climate pattern is part of the stationary Rossby wave train, which is usually generated by the changes of the tropical convection associated with the sea surface temperature variation during El Niño Southern Oscillation (ENSO) cycles. The Rossby wave train is responsible for propagating the ENSO signal to southern high latitudes. Therefore, at the interannual time scale, the Pacific South America pattern is associated with the ENSO variability, creating persistent high (low) pressure centers in the southeast Pacific in response to ENSO warm (cold) events, respectively. This anomalous pressure center consequently has a significant impact on the sea ice variability in the South Pacific and South Atlantic through thermodynamic and dynamic processes.

The ENSO variability in the tropics does not influence the climate variability in the southern hemisphere only through the stationary Rossby waves. It has caused changes and modifications of many aspects of atmospheric circulation in the Southern Ocean, particularly in the South Pacific. For the mean atmospheric circulation, El Niño events generate more vigorous Hadley Cell overturning due to the increased sea surface temperature gradient, accompanied by the stronger subtropical jet and weakened polar front jet in the South Pacific. The Amundsen Low, a dominant variability of surface pressure in the South Pacific that has a strong impact on heat and moisture transports between Antarctica and South pacific, tends to be shallower in response to the warm ENSO events. During La Niña events, storm activities move towards higher latitudes, accompanying a stronger polar front jet, deeper Amundsen Low but a weakened subtropical front jet. Cyclone activities also alter their distributions accordingly: reduced frequencies of cyclones happen over the south Indian Ocean, Australasia, and the Amundsen Sea during El Niño, and vice versa during La Niña events. In association with the Pacific South America pattern and the Rossby wave, blocking highs present another circulation characteristic in the Southeast Pacific influenced by ENSO cycles. The blocking events, usually identified by persistent anomalous high-pressure centers that interrupt the mean zonal flow, frequently occur in both the Southwest Pacific and the Southeast Pacific. In the Southeast Pacific, the blocking highs occur near the high-pressure center of the PSA aforementioned during ENSO warm events. However, the Southern Ocean's response to ENSO variability could change over the time. Studies showed that the net precipitation and moisture budget in the west Antarctic have a positive correlation with the Southern Oscillation index during the 1980s but a negative correlation in the 1990s, implying a decadal change of ENSO teleconnection.

All aforementioned climate modes in the atmosphere interact with sea ice below, producing spatially coherent patterns in the ice field. Sea ice in the Southern Ocean advances from March to September, reaching a maximum extent of about 18 million km^2. More than 80% of the winter sea ice melts in austral summer. Since the late 1970s, satellite passive microwave imagers have been providing continuous sea ice observations in both northern and southern hemispheres. More than 25 years of satellite sea ice observations play a key role in modern climate studies in polar regions. In the Southern Ocean, sea ice not only responds to regional climate variability in the atmosphere, but also is linked to remote forcing in the tropics. The largest interannual variability in Antarctic sea ice is a quasi-standing wave in the western hemisphere called the Antarctic Dipole. The Antarctic Dipole is characterized by out-of-phase temperature and sea ice anomalous centers in the northeastern Ross Gyre in the Pacific sector, and the central Weddell Gyre in the Atlantic sector of the Southern Ocean. The Antarctic Dipole represents the strongest teleconnection between ENSO variability in the tropics and climate variability in southern high latitudes. Temperature anomalies in the Pacific center of the dipole represent the largest ENSO signal in the world outside of the tropical Pacific. In response to ENSO warm events, warmer temperature and less sea ice occur in the Pacific center while colder temperature and more sea ice occur in the Atlantic center of the dipole, vice versa to ENSO cold events. The changes of the basin-scale pole-ward atmospheric heat transport in the South Pacific and South Atlantic, and Pacific South America pattern associated with the ENSO variability are two main mechanisms that directly contribute to the formation of the Antarctic Dipole. After the tropical signal being transported to the southern subpolar regions, temperature and sea ice anomalies grow and amplify reaching their maximum as the southern hemisphere enters its winter. The Antarctic Dipole persists three to four seasons after ENSO matured in the tropics, establishing itself as a distinct high latitude climate mode in temperature and sea ice fields.

Under the influence of atmospheric wavenumber 3 pattern, the similar pattern also exists in the sea ice concentration and sea ice edge, as the second important climate pattern in the ice field. A less dominant pattern is the Antarctic Circumpolar Wave—a wavenumber 2 pattern propagating eastward arguably around Antarctica in sea surface temperature, sea surface height and sea ice. The Antarctic Circumpolar Wave is more visible during the period of 1982–1992 than other times in the satellite era.

In contrast to the Arctic Ocean where sea ice extent has drastically reduced during the last 25 years, Antarctic sea ice extent experiences only a marginally significant increasing trend on average. The most recently documented trend in monthly total ice extent is 8170 ± 3240 km^2/year during the period of 1978–2002. Compared to the maximum ice extent in winter, 18 million km^2, this increasing trend is rather trivial. However, large spatial variability exists in the long-term trend of sea ice around Antarctica. In response to the dramatic warming in the Antarctic Peninsula region, sea ice in the Amundsen Sea, Bellinshausen Sea, and Weddell Sea has significant decreasing trends in its extent, concentration, ice edge, and ice season. In the western Antarctic Peninsula, the early ice retreat in spring and late advance in fall is attributed to the shorter ice season in the recent decade. On the other hand, sea ice extent and ice season in the Ross Sea have experienced significant increasing trends. Even the major climate variability in southern high latitudes, such as the Southern Annular Mode and ENSO related Pacific South America pattern, strongly influence sea ice variability at interannual and longer time scales, but their trends cannot explain the trends in Antarctic sea ice. What causes the trend in Antarctic sea ice, particularly the increasing trend in the Ross Sea ice field, still remains unresolved. Certainly, Antarctic sea ice is very sensitive to global climate. A modeling study suggests that 38% of global mean surface warming for a double CO_2 scenario is due to a change in the sea ice of polar regions. Seventy percent of this change comes from Antarctic sea ice, through changes in sea ice albedo and ease of ice melting. Therefore, any significant changes in future Antarctic sea ice could play a key role in global change.

The most noticeable climate change in the Southern Ocean is the rapid regional warming at the Antarctic Peninsular. At Faraday/Vernadsky station in the western Antarctic Peninsular, surface air temperature exhibits a startling mean warming rate of 2.8°C over the last 50 years, contrasting the global mean warming rate of 0.5°C during the same period. More striking is the warming rate in winter at this station: 5°C–6°C over the last 50 years, the highest rate of warming observed anywhere on earth. The temperature trend gains worldwide attention when the Larsen B ice shelf dramatically and catastrophically collapsed in January–March 2002. The Larsen B ice shelf is now one of seven ice shelves in the Antarctic Peninsula region that collapsed over the last several decades. The collapse of ice shelf also changes the variation of glacier ice sheet behind ice shelf. The summer melting and changes in stress field due to shelf removal become key factors causing the increased glacier flow acceleration towards the ocean, glacier thinning and retreat. However, the rapid warming in the Antarctic Peninsula does not represent temperature changes in the rest of Antarctica. Studies of Antarctic weather station data indicate that rest of Antarctica has a warming rate similar to the global mean. Many coastal stations along the eastern Antarctic and on the plateau of Antarctica surface air temperature even show a moderate cooling, indicating the spatial complexity of changes in recent decades. Satellite observations since the 1970s further confirm the spatial variability of temperature trends. Why Antarctica has such a spatially complicated temperature trend pattern is still an open question.

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SOUTHERN OCEAN: FRONTS AND FRONTAL ZONES

The Southern Ocean contains a series of oceanic fronts, relatively narrow zones of enhanced horizontal gradients of water properties that separate broader, relatively uniform zones with distinctly different vertical structures and water mass characteristics. Most of these fronts are circumpolar, so that anyone traveling to the Antarctic by sea would invariably cross these fronts and notice drastic changes in air and water temperature, weather and ice conditions, ocean color, krill, fish, and sea birds. Some fronts play key roles in various ocean–ice–atmosphere processes. For example, fronts are associated with along-front current jets that transport the bulk of water, heat, and salt. They can meander, forming rings that detach and persist for many months. Fronts are major ecosystem boundaries, often associated with zones of higher biological productivity. Meteorological parameters like surface heat flux and wind stress can change sharply across major thermal fronts, making them important to weather forecasting and climate monitoring. Some Antarctic fronts are related to sea ice conditions, and others can affect the acoustic environment. Sedimentation regimes, largely determined by the ocean circulation, will be related to the distribution of fronts. In addition, sea-born pollutants can be concentrated thousands of times along oceanic fronts.

The northernmost front in the Southern Ocean, sometimes utilized as that ocean's northern boundary, is the Subtropical Front, also called the Subtropical Convergence. This front is found between 30° and 35° S, but is interrupted by Africa, Australia, and South America. Closely spaced hydrographic stations reveal a complex structure consisting of two fronts separated by the Subtropical Frontal Zone. Surface temperature and salinity are generally used to delineate this front, since it is hardly noticeable below 500–1000 m depths. Temperature and salinity characteristics of the frontal zone depend on locations and season. In winter, surface temperature across the front can range from 8°C to 16.9°C, and in summer from 12°C to 19.5°C. Summer surface salinity across the front ranges from 34.3 to 35.58 parts per thousand (or practical salinity units).

The Agulhas Front occurs off South Africa, where it retroflects, extends eastward, and eventually merges with the Crozet Front north of the Crozet Plateau (Del Cano Rise). The Agulhas Front is best defined by the 10°C isotherm, which can vary from $<$300 m to $>$800 m across the front. Another reliable criterion of this front is the presence of a thermostad (thick layer of relatively uniform water) on its warm side, in the 150–300 m layer. A variety of salinity and temperature values have been used in different studies to delineate the front, and these typically change alongstream to reflect substantial cooling and freshening toward the east.

The Subantarctic Front is the northernmost continuous circumpolar front of the Southern Ocean. It marks the southern boundary of a well-developed salinity minimum at ~500–1000 m depths, associated with Antarctic Intermediate Water. A considerable variety of other criteria have been used to identify this front, including a thick ($>$400 m) isothermal layer of sub-Antarctic mode water in the Australian sector, where a double front has also been observed. Considering the strength and robustness of this front, it is surprising that it was ignored for decades until a seminal work by Burling (1961), who distinguished the Subantarctic Front in the Australian–New Zealand region; further studies demonstrated its circumpolar nature. The past situation with this lack of recognition was exacerbated by a terminological confusion, a mix-up between the Subantarctic and Subtropical fronts.

The Polar Front is the northernmost boundary of the subsurface temperature minimum, a hallmark of the Antarctic vertical thermal structure. That minimum is a remnant of winter convection that cools the surface 100–150 m layer, the upper half of which is then capped by summer warming. While the temperature minimum descends and gradually disappears northward, traces of it can occasionally be found as far north as the Subantarctic Front. On meridional vertical temperature sections, the Polar Front is located in summer at the northern terminus of the subsurface temperature minimum, bounded by 2°C isotherm in the 100–300 m layer. In winter it coincides with the vertically oriented 2°C isotherm. In several sectors, more than one Polar Front can be observed, probably accounting for reported positions both north and south of Îles Kerguelen.

The Southern Antarctic Circumpolar Current Front and the Southern Boundary of the Antarctic Circumpolar Current, farther south, were originally defined as intermediate to deep fronts without any surface manifestations. Sea surface signatures have since been reported in some locations. Criteria for the more northerly front have included potential temperature greater than 1.8°C at the temperature maximum at depths greater than 500 m and less than 0°C at the temperature minimum at depths less than 150 m, salinity greater than 34.73 along the salinity maximum at depths greater than 800 m, and dissolved oxygen less than 4.2 ml l-1 along the oxygen minimum at depths greater than 500 m. Not all of these properties are found at all locations. The more southerly front is defined as the southern boundary of the upper Circumpolar Deep Water, the most voluminous water mass in the Southern Ocean. While this front separates different water masses, it is not necessarily associated with enhanced water property gradients.

The Continental Water Boundary has mainly been identified in the upper 500 m near the continental shelf break in the Atlantic sector and may be a local manifestation of the Antarctic Slope Front. It has also been called the Weddell Gyre Boundary. In the Drake Passage it can be identified by a temperature range of 1°C–2°C, salinity range of 33.9–34.0 ppt, and potential density range of 27.1–27.2.

The Weddell-Scotia Confluence, bordered by the Scotia Front and Weddell Front, is a peculiar double frontal zone that forms at the contact between the Weddell Gyre and the Antarctic Circumpolar Current. A characteristic feature is its uniformity, which can be attributed to vigorous vertical and lateral mixing. It is distinguished by a low temperature ($<$0°C), high salinity ($>$34.2), and high potential density anomaly ($>$27.4), with both salinity and density higher that those of adjacent water masses.

The Scotia Front is mainly a regional subsurface feature marked by maximum temperature and salinity gradients along the temperature and salinity maximum core layers of the Circumpolar Deep Water. The temperature maximum decreases southward across the front from 1.5°C–2.0°C to below 0.5°C, while the salinity maximum decreases from 34.70–34.72 ppt to

34.67–34.68 ppt. The most reliable criterion of this front's axis is the 1°C isotherm in the 300–500 m layer.

The Antarctic Ice Boundary Front has been identified only in the Indian sector and appears to form near the northernmost extent of sea ice cover in winter. At that time its surface temperature range is 0°C to –1.8°C, while in summer its temperature range is 2°C–1°C. The surface salinity ranges within 0.1–0.3 ppt. This front can also be detected by a sharp southward cooling and shoaling of the subsurface temperature minimum.

The Bransfield Strait Front is usually associated with the 1.0°C isotherm and 34.1 ppt isohaline, forming a boundary between cold and salty Weddell Sea waters and warm and fresh Bellingshausen Sea waters that enter the strait from opposite sides. Aligned with the main axis of the Strait, this front sometimes extends well beyond 45° E in summer. Outside the Bransfield Strait, the front is oriented along 62° S, parallel to the Southern Antarctic Circumpolar Current front at 60° S.

The Antarctic Slope Front is a distinctive boundary between warm and salty off-shelf waters and cold, fresher or saltier waters of the Antarctic continental shelves. It is best defined below the surface mixed layer, although high-resolution measurements can often pick up subdued surface signatures. This front and an associated westward shelf break current have been reported along much of the circumpolar upper continental slope but are weak in the southeast Pacific sector. Cross-frontal horizontal temperature gradients can exceed 2°C over less than 5 km. A double, V-shaped feature often characterizes the upper front in the Ross and Weddell seas, with colder, fresher water within the V. In locations where the continental shelf is narrow, the frontal zone cannot reliably be distinguished from the northern boundary of the Antarctic Coastal Current. The Antarctic Slope Front extends deep into the water column over the continental slope, where Circumpolar Deep Water is entrained across the front into newly forming Antarctic Bottom Water.

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See also **Antarctic Bottom Water; Antarctic Divergence; Antarctic Intermediate Water; Antarctic Surface Water; Circumpolar Current, Antarctic; Circumpolar Deep Water; Coastal Ocean Currents; Kerguelen Islands (Îles Kerguelen); Marginal Ice Zone; Polar Front**

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SOUTHERN OCEAN: VERTICAL STRUCTURE

The vertical structure of the Southern Ocean, which is ordinary and remarkable in equal measures, is easy to describe. The water density increases with depth and increases towards the south (poleward). Thus, lines of constant density rise towards the south. Water density depends on water temperature and salinity (amount of dissolved salts) so these two properties have a similar structure to that of density. With a few exceptions, temperature decreases while salinity increases with depth and towards the south.

In the ocean, water density must increase with depth so that lighter water will float on heavier. At high latitude, surface water density can increase (for example, by cooling), which causes the upper part of the ocean to overturn. Although these situations are important, they are confined to limited times and places and are not part of the general vertical structure of the ocean. So the increase in density with depth is not remarkable but a property of almost all water in the ocean. The southward increase in density has a similar simple explanation.

Large Scale Vertical Structure

Flow in the Southern Ocean, the Antarctic Circumpolar Current (ACC), is mostly from west to east around the continent of Antarctica. The current is fastest at the surface and decreases with depth due to the drag effect of subsurface seamounts and mountain ranges.

This water movement is governed by a relatively simple force balance (the geostrophic balance) in which horizontal pressure change (or gradient) opposes the Coriolis acceleration. The Coriolis acceleration occurs because we observe the ocean from a moving point of view (the surface of the spinning Earth). It causes objects moving on the surface of the Earth to be deflected. Water in the Southern Hemisphere deflects to the left of its direction of motion; the deflection is larger as the water moves faster.

Pressure in the ocean is due to the weight of the water above it (the hydrostatic balance). In different parts of the ocean, the pressure is different because there is more water (the sea surface is higher) or the overlying water is denser. These horizontal pressure changes try to push water from higher to lower pressure.

The hydrostatic and geostrophic balances are combined to explain the density increase towards the south. The slowing with depth requires that the deeper pressure gradient becomes smaller. The pressure on the south (low pressure) side of the current is increased by increasing the density of the water above. Thus, if the density at any depth level across the Southern Ocean increases towards the south, the flow speed will decrease with depth.

The vertical structure of density in the Southern Ocean is consistent with our dynamical ideas about how the ocean works, so in that sense, it is not remarkable. However, this structure allows water on the north side of the Southern Ocean at a depth of about 4 km to rise to the surface as it moves southward towards the Antarctic Continent. Note that this vertical excursion does not require any change in water density. So, water from deep in the ocean circles around Antarctica side-slipping southward along its density surface until it appears near the surface south of the ACC where it can interact with the atmosphere. Thus, the vertical structure of the Southern Ocean is a critical part of the thermohaline overturning circulation in the World Ocean, which allows deep water to move to the surface where it is changed—a remarkable property indeed.

Distinct Water Types and the Thermohaline Circulation

Water in the ocean has distinctive values of temperature and salinity. Water properties are set at the surface in a limited number of places in the World Ocean where the surface water density is increased sufficiently for it to move into the ocean interior, sometimes all the way to the bottom. Once the water is away from the ocean surface, its properties change only slowly due to relatively weak internal mixing.

Water types are named by their observed depth and place of origin. For example, very salty and cold (near freezing) water is produced at several places around the Antarctic Continent. This water slides off the continental shelf (and mixes a bit on the way down) to produce the densest water in the ocean—Antarctic Bottom Water (AABW). The very cold water (around –0.8°C) at the bottom of the Weddell Sea is an example of AABW.

Another dense water type (North Atlantic Deep Water or NADW) is created in the North Atlantic between Greenland and Norway by severe winter cooling (and freezing of sea ice). This water, which fills the deep parts of the North Atlantic, is warmer and saltier (and less dense) than AABW. NADW moves southward in the Atlantic Ocean above AABW. Circumpolar Deep Water (CDW) is a slightly modified form of NADW, which is identified by higher temperature and salinity compared to surrounding waters. It is mainly this water that climbs along the sloping density surfaces of the Southern Ocean. This water can be traced by the high salinity at 3 km depth, which rises to the surface on the south side of the ACC.

At the surface, CDW is made colder and fresher to produce Antarctic Surface Water (AASW). Surface wind forcing and the Coriolis acceleration, push

AASW northward until it finds a density horizon matching its own density, at which point it sinks below the surface as Antarctic Intermediate Water (AAIW). This cold and somewhat fresh water proceeds northward in the Atlantic Ocean to return to the North Atlantic where it closes one part of the global thermohaline overturning cell. The northward flowing surface water, driven by the wind, is the mechanism that pulls the CDW up from depth.

The interplay of heat change (heating by solar radiation; cooling by infrared radiation, evaporation and contact with the cold atmosphere) and salinity change (decrease by precipitation and melting of sea ice; increase by freezing of sea ice) creates surface water density changes, which results in an elaborate three-dimensional circulation in the World Ocean. Wind forcing at the ocean surface also helps drive this large scale circulation. The Southern Ocean is a critical element of that circulation and its observed vertical structure is the result of (or at least allows) the circulation.

Seasonal Changes in Vertical Structure

Due to its high latitude, the Southern Ocean experiences a strong seasonal change in sunlight, being largely absent in the winter and continuously available in the summer. This pattern leads to strong warming of the surface water in the summer and equivalent cooling (to the cold atmosphere) in the winter. The winters are so severe that the surface of the ocean freezes over about half of the Southern Ocean. This cycle has a strong influence only on the upper ocean (to a depth of 100 m or so) with almost no effect on the water below. Over most of the Southern Ocean, this seasonal cycle of solar heating and atmospheric cooling creates a cold layer at the ocean surface in winter of 50 to a few hundred meters thick and a warm layer in summer of 10–40 m thick. Winds over the Southern Ocean are stronger in spring and fall and weaker in summer and winter. These changes in wind strength change the depth of mixing near the surface of the ocean by a few tens of meters but otherwise do not cause a strong seasonal change in the vertical structure of the ocean.

During the winter in the southern half of the Southern Ocean, the water from the surface down to about 100 m cools to the freezing point (about –1.8°C). In a few places, this cooling creates water dense enough to mix to 400–600 m depth. Next to the Antarctic Continent, intense cooling due to katabatic winds (very cold air draining off the Antarctic Polar Plateau) creates very cold and salty water that falls to the bottom (around 500 m) and eventually flows off the shelf to create AABW.

As the surface water freezes to make sea ice, most of the salt accumulates in brine which flows into the ocean increasing the salinity of the upper ocean. However, in the spring the sea ice melts releasing the water back to the ocean and almost balancing the salt release in the winter. There is a small seasonal change in the surface salinity (a few hundredths of a percent) due to this seasonal melt-freeze cycle of sea ice.

The ACC is constrained to flow through Drake Passage, south of South America, which is the narrowest constriction to the flow (about 800 km wide). More importantly, the ACC flows along several mid-ocean ridges and is constrained to pass through several narrow gaps in these ridges, for example the Udintsev Fracture in the South Pacific Ocean. In spite of these constrictions and the perturbations that they cause, the vertical structure of the Southern Ocean maintains the general pattern seen at the Greenwich Meridian. Thus, the observed vertical structure is resistant to change. Since there are many ways that the structure might change (mixing, topographic effects, speed changes, surface forcing, etc.), we must conclude that the processes that create this vertical structure remain active, constantly pushing the Southern Ocean into the state that we see.

The smooth structure of the water properties in the Southern Ocean is broken by several narrow fronts, which are locations of strong horizontal change in water properties. From north to south, the Southern Ocean fronts are the Subantarctic Front (SAF), the Polar Front (PF), the Southern ACC Front (SACCF), and the southern boundary of the ACC (SBndy). As with much of oceanography, different names are chosen at different times or by different investigators. For example, the Polar Front has been called the Antarctic Convergence by some authors, though this term is now rarely used. All of these fronts are continuous around the Southern Ocean.

ACC fronts are distinct from other oceanic fronts in that they extend throughout the water depth. Because water density changes across these fronts, they are also zones of strong horizontal pressure change, which gives rise to narrow, fast currents (referred to as "jets"). Southern Ocean fronts are locations of strong flow in addition to being transition zones for water properties.

Frontal jets introduce another complicating factor to the oceanography of the Southern Ocean: frontal meanders. Rapid, narrow flows in an otherwise still ocean are susceptible to wiggling (or meanders), which develops into extended loops of current that wrap around on themselves producing a ring of current called an eddy.

These eddies are essential to the way that the ACC works. An eddy acts as a sort of container (or thermos bottle) transporting water properties (like heat, salt, nutrients, and momentum) across the ACC. Thus, the presence of the narrow jets allows the creation of eddies which produces the movement of properties across this broad flow that circles the Earth. These eddies are thought to be a part of the process that creates the fronts in the first place!

There is considerable study at present on the processes that drive the circulation in the Southern Ocean and produce the structure and variability of the flow and water properties that are observed. These efforts involve computer models as well as observations. Questions now being addresses are the size and reason for the changes in the speed of the ACC, the effect of changing sea ice on the ocean, the importance of the ocean in melting the ice over the Antarctic Continent, the role played by the Southern Ocean in the global thermohaline circulation, and others.

Computer-based numerical ocean circulation models are being used by many groups to study various aspects of the oceanography of the Southern Ocean. Some of the models consider the Southern Ocean in isolation from the rest of the World Ocean while others represent the whole (global) system. Most circulation models are driven by the atmosphere (and solar radiation). Some studies couple freely evolving atmosphere and ocean models allowing the two parts of the global system to interact. Both types of model approaches allow the study of the changes to the Southern Ocean vertical structure that would be expected from variations in the ocean-atmosphere-cryosphere that have been observed as past climate changes.

Vigorous observational programs measure the structure and variability of the water properties and the circulation over many parts of the Southern Ocean. Some measurements are based in the ocean (attached to moorings or based on ships) while others are taken through sensors on satellites.

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See also **Antarctic Bottom Water; Antarctic Intermediate Water; Antarctic Surface Water; Circumpolar Current, Antarctic; Circumpolar Deep Water; Coastal Ocean Currents; Eddies in the Southern Ocean; Southern Ocean; Southern Ocean: Bathymetry; Southern Ocean Circulation: Modeling; Southern Ocean: Fronts and Frontal Zones; Thermohaline and Wind-Driven Circulations in the Southern Ocean**

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SOUTHERN RIGHT WHALE

The southern right whale *(Eubalaena australis)* belongs to the Balaenidae family. Members of this family are characterised by a narrow, highly arched upper jaw and long baleen (the large food filter plates that hang from the roof of its mouth). The earliest known balaenid fossil, discovered in South America, is early Miocene ($\sim$25 Ma; Fordyce and Barnes 1994). There are many later Miocene and Pliocene records of Balaenidae from around the North Atlantic and the North Pacific. However, the fossil records offer no obvious clues to the origins of right whales.

There are three taxonomically recognised species of right whales: the North Atlantic right whale *(Eubalaena glacialis),* the North Pacific right whale *(E. japonica),* and the southern right whale *(E. australis)*. Because of differences in timing of southern and northern breeding seasons and apparent discontinuity of distribution across the Equator, there appears to be no mixing between the Northern and Southern Hemisphere taxa. The presence of an intervening continent also precludes mixing between North Atlantic and North Pacific right whales. Recent genetic studies further suggest reproductive isolation between North Atlantic, North Pacific, and South Atlantic right whales (Rosenbaum et al. 2000).

Southern right whales are large, stocky baleen whales that weigh between 40 and 80 tons. They are identified by their black colouration, lack of dorsal fin or ridge, and the presence of callosities on their heads. The callosities are outgrowths of tough, cornified skin to which cyamid amphipods (or whale lice) attach. These cyamids survive by apparently feeding on whale skin. Barnacles are also present on callosities of right whales in some populations (e.g., South Africa). Roger Payne first recognised that the head callosities formed different patterns on individual whales that changed little over time. This special feature became a useful form of individual identification in population studies (Payne et al. 1983).

These whales are easily recognisable from other whales at a distance at sea, as their widely separated nostrils create a V-shaped blow when they exhale. Their cruising speed is between 5 and 8 km h^{-1} (2–3 knots).

Adult southern right whales measure between 12 m and 16 m in length. There are no obvious differences between sexes, although females are usually slightly larger than males, and Payne found that males may have more and larger callosities on their heads than females.

Although southern right whales are predominantly black with occasional white blazes on their belly and chin, some whales also show variation in pigmentation, including light brown, mottled gray, and white dorsal markings such as spots and blazes. White-phased calves have been reported in several populations. These calves turn into light gray animals as adults.

The right whale is so named because it was considered to be the "right" whale to hunt. It was slow-moving, so easier to reach, it had plentiful oil and baleen, and its buoyancy meant that it floated when harpooned. Therefore it became one of the most hunted of all species of whales.

As a result of worldwide exploitation, southern right whales have been reduced to levels less than 10% of their original abundance. First hunted in the early 1600s along the Brazilian coast, the spread of pelagic whaling to other grounds in the late 1700s and early 1800s rapidly depleted species numbers. Despite gaining international protection in 1935, this species continued to be hunted illegally by the Soviet Union until the 1970s. The species currently numbers around 8000 individuals and is listed as "threatened" by the IUCN.

The southern right whale has a circumpolar distribution and generally inhabits sub-Antarctic water between about 20° and 55° S, although they have been seen as far as 63° S. They appear in coastal waters in winter months to mate, calve, and rear their young, and tend to migrate offshore to feeding grounds during summer months when supplies of krill are greater.

Historic calving grounds include areas in Mozambique, Tristan da Cunha, Namibia, Angola, Chile/Peru, Îles Crozet, the central Indian Ocean (around Île St. Paul), the New Zealand mainland, the New Zealand sub-Antarctic, the coastal waters off South Africa, Argentina (Península Valdés), southern Brazil, and off the coast of southeast and southwest Australia. Currently, only the later six of these calving grounds are showing signs of recovery from whaling. Based on aerial surveys conducted by Peter Best, the South Africa population is increasing at an average rate of 7% each year, and the total population size is around 3100 animals. Surveys by Payne show a similar rate of increase for the Argentina population, with a population size of about 2500 whales. In the waters of south and western Australia, the rate of increase has been estimated at 7%–13% per annum, and the population size of the entire Australian population is around 1000 individuals. The New Zealand sub-Antarctic population numbers less than 1000, and the Brazilian population in the low hundreds (International Whaling Commission 2001).

In the Northern Hemisphere, there appears to be a north–south migration between low-latitude calving grounds and high-latitude feeding grounds. In the Southern Hemisphere, the migration patterns between winter calving and summer feeding grounds are less clearly associated with latitudinal clines. There appears to be some north–south migration (e.g., South African calving ground to subtropical convergence feeding grounds) as well as some east–west movements (e.g., South Africa calving ground to Gough Island feeding grounds) (Best et al. 1993). The recent resighting in waters at 64°26′ S of an animal previously identified in Western Australian waters provided the first evidence of direct movement between Antarctic feedings grounds and winter coastal breeding grounds (Bannister et al. 1999).

Baleen whales have two main feeding techniques: lunge-feeding and skim-feeding. Lunge-feeders feed by engulfing a vast volume of water and then filtering their prey (krill and/or fish) by pushing the water through their baleen. These include whales with ventral pleats such as humpback, minke, fin, Bryde's, and blue whales. Right whales, like bowheads and sei whales, are skim-feeders, which is open-mouth slow skimming through dense patches of prey (krill) at or near the surface, filtering the water. Inside each side of a right whale's mouth are 200–270 long, thin baleen plates that may reach up to 3 m in length. These finely fringed plates act as a sieve during feeding, retaining zooplanktonic prey species.

Southern right whale courtship behaviour can be very spectacular. It may involve waving of flippers, breaching (leaping out of the water), tail slapping, stroking, splashing, rolling over, and rubbing each other. Courtship of a female right whale may take many days, and the females may mate with more than one male.

Male right whales do not occupy breeding territories or sing like humpback whales; rather females apparently vocalize to attract males. There is no apparent aggressive behaviour between males during courting bouts. The male right whales have enormous testes in proportion to their body weight. This suggests that the mating system involves sperm competition where males compete to inseminate females not by physical aggression but by delivering large quantities of sperm and displacing that of other males.

The age of sexual maturity varies between females and males. Age of sexual maturity for female southern right whales ranges from 6 to 13 years, with a mean of 9 years. This is based on long-term photo-identification studies by Best and Payne, where female calves were photographed and seen with their own first calf years later. No such information exists for males. However, it is thought that males mature earlier, probably between 3 and 6 years of age.

The duration of gestation is about 1 year, and only one calf is produced at a time. When the calf is born, it will measure between 5 and 6 meters and weigh 1000 kg. The calf is born tail-first and is gently nudged to the surface to take its first breath. The newborn calves have virtually no blubber to insulate them from the cold and must put on fat quickly. The calf does not suckle per se; rather the mother squirts the milk into the calf's mouth from a nipple on her ventral surface. The mother's milk has a 40% fat content, and a right whale calf can consume up to 600 liters of this rich milk per day. As a result, a right whale calf may add 50 kg per day and grow 1 m per month for the first few months of its life.

However, during this time the mother will fast, as there is little food available on the calving grounds. The demands of gestation, birth, and care are such that after one year of gestation and one year of weaning, a mother will take a full year to recover before she is ready for the next pregnancy. Thus mean calving interval in southern right whales is approximately 3 years.

Calves stay close to their mothers and will do so for up to a year or more until they are weaned. During this time the bond between the mother and calf is very strong. Southern right whale females will always place themselves between the calf and danger. Unfortunately, this motherly instinct was severely exploited by whalers who targeted calves, knowing that once secured, mothers would not leave.

The maximum life span for right whales is unknown but is likely to be 90–100 years. Little is known about natural mortality in southern right whales. Killer whales and sharks are the only known predators.

Nathalie Patenaude

See also **Blue Whale; Crozet Islands (Îles Crozet); Fin Whale; Gough Island; Humpback Whale; Minke Whale (Antarctic Minke Whale); Sei Whale; St. Paul Island (Île St. Paul); Whales: Overview; Whaling, History of; Zooplankton and Krill**

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SPAIN: ANTARCTIC PROGRAM

The Antarctic Program of Spain was officially established in 1988. At that date Antarctic scientific research was included into the quadrennial Research and Development National Plan, and it has continued this way.

Previously, historical Spanish expeditions (as the Gabriel de Castilla one in 1603 or the tragedy of *San Telmo* in 1819) were documented, and the scientists' work was hosted by Antarctic programs of other countries. In 1986–1987 and 1987–1988 two Spanish Antarctic expeditions to Scotia and Bransfield seas took place.

Spain ratified the Antarctic Treaty in 1982 and became a Consultative Party in 1988. In January 1988, the first Spanish Antarctic station, named Juan Carlos I, was established at 60°23′20″ W, 62°39′46″ S, in Hurd Peninsula, in the southern coastal area of Livingston Island, South Shetland Islands. It has a total building surface of about 390 m^2, with 85 m^2

dedicated to laboratories. It is a summer station that is normally open from late November to early March. Its sixteen places are usually occupied half by scientists and half by technician personnel.

A second Spanish station, Gabriel de Castilla, was established in 1989 at 60°40′30″ W, 62°58′40″ S, close to the western coast of Port Foster, in Deception Island, South Shetland Islands. Its total building surface is 290 m^2, of which 93 m^2 is dedicated to laboratories. It is open every year during the same period as Juan Carlos I station, having a similar number of places and type of occupation.

During the first three campaigns after the establishment of the Spanish Antarctic Program (1988–1991), Spanish expeditions were supported by the vessel *Las Palmas*. This 1978 ship is 41.2 m in length and has a displacement of 1500 Tm. The 1991–1992 season was the first one for the new R/V *Hesperides*. This modern ice-strengthened multipurpose ship was built in 1991 and has an overall length of 82.5 m, 14.3 m breadth and 2700 Tm displacement. It has 665 m^2 of laboratories and room for thirty scientists, apart of the crew. Its equipment includes multibeam and other echo sounders, seismic multichannel systems, and other modern instruments for geological, biological, and physical oceanographic researches.

After a modernization of *Las Palmas* that increased its passenger capacity to twenty places, it returned to Antarctica as a support vessel for the Spanish expeditions. Since the 2000–2001 season *Las Palmas* and *Hesperides* have taken part at the same time in the Spanish Antarctic campaigns, except in 2003–2004, when Hesperides was not able to participate due to half-life maintenance and modernization operations.

The Spanish Antarctic program depends at present on the Ministry of Education and Science. Every year a call for research projects is officially published. Proposals can come from universities and public research organisations and institutes. They are evaluated by pairs at the National Evaluation Agency (ANEP) and later selected by a committee. To date, participating researchers have come from twenty universities, six institutes of the Scientific Research Council (CSIC), and six other public research organisations.

The coordination of the Antarctic program, the selection of the scientific projects, and the vessels' calendar is determined by the Ministry of Education and Science. Juan Carlos I station is operated by the Scientific Research Council (CSIC), Gabriel de Castilla station by the Spanish Army, and the two vessels by the Spanish Navy. The Ministry of Foreign Affairs is responsible for relationships with the Antarctic Treaty Consultative Meetings.

In 1998 the Spanish Polar Committee was established to coordinate the different ministries involved in Antarctic activities. At present this committee is located at the Ministry of Education and Science. A National Antarctic Data Centre was also set up in 1999, including a polar library and a bank of metadata related to the Spanish Antarctic research, being linked to the Antarctic Master Directory. Information about the mentioned organization, environmental procedures, stations and vessels can be found at www.mcyt.es/cpe.

Although it is difficult to have an accurate figure for the total expenditure of Spain in Antarctic activities, due to the participation of different organizations, a mean annual figure of about 3.5 million Euros could be estimated for recent years. This includes costs of science and operations but not staff, crews, station personnel, and scientists' salaries, as well as other costs borne by the involved organisations.

Spain became an associate member of the Scientific Committee on Antarctic Research (SCAR) in 1987 and a full member in 1990. Since then, the annual SCAR reports from Spain collect the data of the research projects carried out and identify the research groups. In 2003 the composition of the Spanish SCAR Committee was adapted to the new structure adopted by SCAR after its review. Spain is also a member of the Council of Managers of National Antarctic Programs.

An overview of the subjects of the Spanish Antarctic Research can be obtained by means of the published results. A compilation and analysis of the Antarctic publications by Spanish authors up to 2001 has been published (López-Martínez and Durán 2002). It contains 936 references, including 830 scientific and 106 informative publications. More than 98% of the references belong to the 15-year period between 1987 and 2001. Marine researches cover 55% of the scientific publications. Subjects of publications are biology (42%), geology and geophysics (30%), atmosphere (7%), oceanography (5%), glaciology (4%), cartography and mapping (3%), and miscellaneous (9%).

Spain ratified the Protocol on Environmental Protection to the Antarctic Treaty in 1992 and is a member of the Committee on Environmental Protection. Procedures for environmental impact assessment, issue of permits, and fulfilling the Protocol recommendations have been established for Spanish Antarctic activities.

JERÓNIMO LÓPEZ-MARTÍNEZ

See also **Antarctic Treaty System; Council of Managers of National Antarctic Programs (COMNAP); Deception Island; Protocol on Environmental Protection to the Antarctic Treaty; Scientific Committee on Antarctic Research (SCAR); South Shetland Islands**

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SPRINGTAILS

Springtails (Collembola) are the most numerous, and after mites the most diverse, group of terrestrial arthropods in the Antarctic. However, they are easily overlooked as they are small (adults being at most 2 mm long) and cryptic in habit, but extremely widespread animals that can be very abundant at a local level. There are about 8000 species known globally in thirty families and nearly 600 genera, but the world fauna is estimated at 50,000 species (Hopkin 1997).

The morphology of Collembola is similar to insects as they have a body divided into three parts, a head with one pair of jointed antennae and two pairs of mouthparts, a three-segmented thorax with a pair of jointed legs on each segment, and a segmented abdomen with paired appendages ventrally on some segments. They differ in being soft bodied, in lacking a hard exoskeleton and wings, in the mouthparts being internal, and in possessing simple eyes, maximally eight, on each side of the head. Uniquely, Collembola possess a ventral tube ventrally on abdomen I and a paired jumping organ ventrally on abdomen III, hence the name Springtail. The ventral tube regulates osmotic conditions and is adhesive in some species. Antarctic species are white, black, or grey.

Two of the three orders are represented in Antarctica. The Arthropleona, to which most species belong, are elongate with the majority of the body segments separate and equal in length, and the rarer Symphypleona are globular with anterior body segments fused.

The first species described from Antarctica were by Willem in 1901 from the Peninsula; *Cryptopygus antarcticus* and *Isotoma octooculata* (now *Folsomotoma octooctulata*) and in the next year *Isotoma klovstadi* by Carpenter in 1902 from Victoria Land, all Isotomidae. Twelve species are now known from Victoria Land, including one probable translocation and one not fully described, two species from Queen Maud Land including the same probable translocation, and fifteen from the Antarctic Peninsula and Maritime Antarctic. Of the latter, two are probable synonyms and one an incorrect identification, leaving twelve. Endemism is highest in Victoria Land with six endemic genera and all ten species endemic contrasting with no endemic genera and only six endemic species in genera *Friesea* (Neanuridae), *Cryptopygus,* and *Tullbergia* (Onychiuridae) in the other regions (Greenslade 1985, and unpublished data). Current genetic studies suggest that cryptic, sibling, but parapatric, species occur so numbers may be revised upwards in future (Stevens and Hogg, in press).

Collembola only live in ice-free areas, in soil, under stones, in mosses and algae and other vegetation and interstitially in the marine littoral zone. High densities can be found in some habitats and up to 500,000 individuals of *C. antarcticus* per m^2 have been recorded in soil under the grass *Deschampsia*. The most widespread, abundant, and speciose genera are *Cryptopygus* (Isotomidae), *Friesea* (Neanuridae), and *Tullbergia*. (Onychiuridae). Species of *Cryptopygus* feed on filamentous fungi and algae, *Friesea* on rotifers, and *Tullbergia* in the mycorrhizal zone. As no macrodetrivores occur, Collembola play a larger role in nutrient cycling than in temperate regions. Predators of Collembola here are few and comprise mesostigmatid and prostigmatid mites.

The ecology and physiology, including cold tolerance, of a few species, notably *C. antarcticus, F. octooculata, I. klovstadi,* and *Gomphiocephalus hodgsoni* (Carpenter 1908) (Hypogastruridae) have been studied. All show adaptation to cold desert conditions by reducing water content and synthesising thermal hysteresis proteins, polysaccharides such as lactose and trehalose, and avoiding ice nucleation (Block 1997; Sinclair et al. 2003). Cold conditions induce inactivity resulting in longevity, with *G. hodgsoni* individuals able to survive 2 years and *C. antarcticus* over 3.

Penelope Greenslade

See also **Algae; Mosses; Soils**

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SQUID

Since the search for Antarctic cephalopods began onboard the *Challenger* Expeditions in 1872, about eighteen species of squid spanning thirteen families have been identified in the Southern Ocean. In the early years, knowledge of squid was based on fragments of specimens or remains found in the stomachs of predators, particularly certain whales. In more recent years, the development of scientific and commercial fishing methods and studies of land-based predator diets has revealed more about the biology and ecology of Southern Ocean squid. Compared with those at lower latitudes, Southern Ocean squids are represented by just one of the two suborders (Oegopsida) and many families of this oceanic group (that are normally abundant in temperate areas) are absent. Although the reasons for these differences are not clear, it has been suggested that low water temperatures and the vast sea ice belt around Antarctica is responsible for the absence of the neritic Myopsida. This group lays egg masses in shallow, coastal waters which, together with long development times that are typical of Southern Ocean species, would make them susceptible to ice scour. The Southern Ocean squid fauna, like other marine invertebrates there, show a high degree of endemism, meaning that the endemics are found nowhere else in the world's oceans. This is probably a result of the long evolutionary history of the Southern Ocean and the formation of the Polar Front that acts as a biological barrier between the cold Antarctic waters and the warmer sub-Antarctic waters.

Southern Ocean squids are predominantly pelagic, ranging in depth from a few metres below the surface to the deep ocean, and their distribution may be influenced by physical factors such as water masses, sea ice extent, and bathymetry. Some species are restricted to waters south of the Polar Front *(Psychroteuthis glacialis, Galiteuthis glacialis, Kondokovia longimana, Alluroteuthis antarcticus, Moroteuthis knipovitchi, Brachioteuthis picta, Histoteuthis eltaninae, Batoteuthis skolops,* and *Mastigoteuthis psychrophila),* whilst other deep-water species (e.g., *Chiroteuthis verenyi*) and highly mobile, migratory species (e.g., *Martialia hyadesi* and *Moroteuthis ingens*) are found either side of it. Species with circumpolar distributions include *Galiteuthis glacialis, Mesonychoteuthis hamiltoni, Psychroteuthis glacialis, Alluroteuthis antarcticus, Kondokovia longimana,* and *Moroteuthis knipovitchi*. All species occur in oceanic waters, but some are found in coastal waters (e.g., *Alluroteuthis antarcticus, Histoteuthis eltaninae* and *Psychroteuthis glacialis*), around groups of islands (e.g., *Moroteuthis knipovitchi*), continental shelves (e.g., *Moroteuthis ingens, Galiteuthis glacialis,* and *Martialia hyadesi*), and the slopes of continental shelves (e.g., *Galiteuthis glacialis, Histoteuthis eltaninae, Todarodes filippovae,* and *Psychroteuthis glacialis*). There still remain vast areas of the Southern Ocean for which there is little or no data on squid distribution.

Although many squid species undertake daily, ontogenetic and long-distance migrations, there are insufficient data to interpret the migratory patterns of most Antarctic species. *Slosarczykovia circumantarctica* and *Gonatus antarcticus* are known to undertake vertical migrations from deep water (400 m and 525–1000 m, respectively) during the day to shallow water (subsurface and 60–200 m, respectively) at night, possibly to avoid visual predators. *Galiteuthis glacialis* and *Alluroteuthis antarcticus* also undertake vertical ontogenetic migrations from shallow to deep water as they mature. It is likely that Southern Ocean squids undertake long-distance migrations that are typical of temperate and tropical oegopsids. Passive migration in Southern Ocean currents may distribute eggs and paralarvae downstream, where after juveniles and adults may actively migrate towards feeding grounds and then upstream to their original spawning grounds to complete their life cycle.

Relatively little is known about the life-cycle and growth of Southern Ocean squid. Standard methods for measuring growth have yet to be validated for Antarctic species. It has been suggested that, owing to low temperatures, Antarctic squid may experience lower growth rates and live longer than the 1-year lifespan typical of their temperate and tropical zone counterparts. *Kondokovia longimana* and *Mesonychoteuthis hamiltoni* also reach very large sizes (over 1 and 2 metres in mantle length, respectively) and are therefore likely to live longer than 1 year. Southern Ocean squid appear to produce larger eggs and have longer development times than temperate counterparts (as shown in benthic invertebrates). The maturation and spawning patterns of Southern Ocean squid are unknown, but the presence of distinct size classes in populations of *Psychroteuthis glacialis* and *Galiteuthis* *glacialis,* and the size frequency of eggs in the ovaries of *G. glacialis,* suggest discrete spawning periods.

Squid appear to play an important role in the Southern Ocean food web as both predators and prey. They form an important food source for marine mammals, seabirds, fish, and other cephalopods. Southern Ocean whales, seals, and seabirds have been estimated to consume ~28 million tonnes of squid per annum. In comparison, global fisheries land an average of 2 million tonnes of squid per annum. Less is known about the diet of Southern Ocean squid, and only *Moroteuthis ingens* and *Martialia hyadesi* have been studied in any detail. Most species, however, appear to consume a wide variety of prey including crustaceans (e.g., krill, hyperid amphipods, and mysids), fish (e.g., myctophids and gonostomatids), and squid (including cannibalism). In common with many squid species, they also appear to shift from predation upon crustaceans to fish and squid with increasing body size.

There are currently no commercial fisheries for Southern Ocean squid. There has been commercial interest in two Southern Ocean ommastrephid species (*Martialia hyadesi* and *Todarodes fillipovae*) but exploratory fisheries have not produced consistent catches. Should any fishery for these species develop in the Southern Ocean, they would be overseen by the Commission for the Conservation of Antarctic Marine Living Resources, which takes an ecosystem approach to fisheries management.

NADINE M. JOHNSTON

See also **Albatrosses: Overview; *Challenger* Expedition (1872–1876); Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Deep Sea; Fish: Overview; Food Web, Marine; Growth; Pelagic Communities of the Southern Ocean; Polar Front; Reproduction; Seals: Overview; Whales: Overview; Zooplankton and Krill**

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ST. PAUL ISLAND (ÎLE ST. PAUL)

Île St. Paul is not an Antarctic island. Located in the Indian Ocean at 77°30′ E, 38°44′ S, it is 90 km to the southwest of Amsterdam Island and 3000 km to the south of the Réunion.

Probably discovered in 1559 by Portuguese sailors, it is supposed to have been visited for the first time by a Dutchman called Vlaming in 1696. There are also traces left from a village of French fishermen from the Réunion dating back to 1843. Today, it is a deserted island.

This extinct volcano with a triangular shape and an area of 7 km^2 (3 km from West to East and 5 km from North to South), is a breached crater that opens onto the sea in the northeast. The thin rocky stretch that used to close the crater collapsed in 1780, letting in the sea through a channel less than 100 m. This rocky block now lies only a few meters under water, which allows only very small ships to enter. The interior basin, 1 km wide and 50 m deep, with continually still waters, is splendid. The internal walls of the crater are almost perpendicular all around, up to 270 m. From this height, winds can blow in heavy gales, with moments of respite, which makes for very dangerous anchoring.

The crater is protected from the sea by to low jetties made up of rocks, one 200 m and the other 500 m. All around, the island gradually lowers up to a cliff about 100 m high that dominates the seashore. Right outside the basin, to the north of the channel, a remarkable great rock 83 m high, called La Quille, consists of horizontal strata of variegated colors. Other rocks are like balsatic columns, proofs of past lava flows.

The vegetation is sparse, made up mostly of graminaceae. The intense violence of the winds and the total lack of shelter prevent the growth of species of a certain height. As for the fauna, fur seals, exterminated for their fur in the nineteenth century, are now back in numbers, feeding profusely on the abundant fish. Numerous rockhooper penguins, petrels (blue petrels, white-bellied storm petrels, and Antarctic petrels), terns (Antarctic and sooty), some great skuas, and a few sooty and yellow-nosed albatrosses can also be found on the island.

Large supplies of sea crayfish around the island are now controlled, with three or four French factory-ships having official fishing permits to be renewed yearly.

Île St. Paul has been described many times as ships sailed by. The *Novara,* an Austrian training ship sailed in front of St. Paul for 2 weeks in 1857 and drew the first good map of the island. In 1874, a French astronomical mission was set up there for 2 months to observe the transit of Venus in front of the sun. A young geologist, Charles Vélain, took this opportunity to make a significant geological survey of the island.

Île St. Paul definitively became French in 1893. With Amsterdam Island, it is part of the district of the Overseas Territory of the Southern and Antarctic French Lands (Territoire d'Outre Mer des Terres Australes et Antarctiques Françaises; TAAF) under the authority of a senior administrator who lives in the Réunion. A science base of about twenty people has been on Amsterdam Island since 1949, but today Île St. Paul is home to only a few scientists on temporary missions and researching specific projects.

GRACIE DELÉPINE

See also **Amsterdam Island (Île Amsterdam); France: Antarctic Program; Sub-Antarctic Fur Seal**

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STREAMS AND LAKES

Although most of the Antarctic continent is deep frozen and offers little opportunity for aquatic life, air temperatures around the margins of the continent rise above zero each summer and allow a remarkable diversity of lakes, ponds, and streams to develop and persist. Some of the lakes are freshwater and are fed by the melting snowpack and glaciers, while others contain saline bottom waters that are overlain by freshwater and further capped and insulated by thick, perennial ice. The streams typically flow for only a few weeks to months each year before refreezing and often show large variations in discharge associated with seasonal and daily fluctuations in solar radiation. The extreme biogeographical isolation of all of these environments in combination with the severe conditions of light, temperature, and freeze-thaw cycles has strongly influenced their biota. These ecosystems contain truncated food webs in which fish are absent. Unlike equivalent habitats in the Arctic, even arthropod communities (insects and crustaceans) are limited in distribution and diversity, although a few species can reach large population densities at some locations. Many types of microscopic life-forms survive, grow, and even thrive in these unusual environments. Antarctic lakes and streams are proving to be useful model systems for the wider understanding of microbial, biogeochemical, and ecological processes, as well as sources of novel microbes for research and biotechnology.

The early explorers to the McMurdo Dry Valleys region of Antarctica noted that the valleys contained frozen lakes, with evidence of brightly coloured plants growing in the waters beneath the thick ice. Research on these waters subsequently showed that these were meromictic lakes, so-called because they never completely mix. Their 3–7 m thick ice cover persists through summer and protects them from the wind, and their dense saline bottom waters remain stagnant and without oxygen throughout the year. These lakes act as natural greenhouses, and over a period of millennia the deeper waters have trapped solar energy, heating to surprisingly warm temperatures. The extreme example is Lake Vanda, in the Wright Valley. Its surface waters are cool and fed by the Onyx River that flows 30 km inland from the Lower Wright Glacier. However its bottom waters, 70 m beneath the ice cover, are three times saltier than seawater, and long term solar heating has resulted in temperatures up to 25°C. The Dry Valley lakes are highly structured in their chemistry and microbiology, with layers of different microbial communities at different depths. The photosynthetic communities include flagellated algae from diverse phyla in the upper water column such as *Chlamydomonas, Pyramimonas, Chroomonas,* and *Ochromonas,* and a thick layer of orange or pink mats of cyanobacteria growing on the sediments. The latter are the "water plants" observed through the ice, and their pigments include the red protein phycoerythrin to capture low levels of sunlight for photosynthesis, and orange carotenoids to protect them from bright sunlight including harmful UV-B radiation. Some of these algal mats precipitate a calcium carbonate crust as they photosynthesize, leading researchers to label them "living stromatolites" that closely resemble the earliest fossils of life on Earth. A microscopic consortium of cyanobacteria and heterotrophic bacteria has also been discovered to reside in pockets of meltwater contained within the lake ice.

Subsequent exploration of the continent has revealed several regions containing saline lakes, notably in the Vestfold Hills, Bunger Hills, and Langhovde (near Syowa Station). Isostatic uplift in those regions has resulted in trapped basins of seawater that have been subsequently overlain by dilute meltwaters. Unlike the Dry Valleys ecosystems, the saline lakes and lagoons contain small planktonic animals (zooplankton), in particular the calanoid copepods *Drepanopus bispinosus* (restricted to seasonally isolated marine systems) and *Paralabidocera antarctica*. One of the Vestfold Hills lakes is so saline (Deep Lake) that it never freezes up, and in late winter its hypersaline waters cool to –18°C yet remain ice-free. Freshwater lakes also occur in these regions and contain the 2.5 mm-long water flea (cladoceran) *Daphniopsis studeri* and the copepod *Acanthocyclops mirnyi.*

One other class of saline-brackish waters in Antarctica is epishelf lakes. These are formed by a floating ice shelf blocking the mouth of a fjord or embayment, and although they are mostly restricted to several locations in Antarctica, a few examples are also known from the Arctic. These lakes are contiguous with the sea beneath the ice shelf and are therefore tidal. Their surface waters, however, are fed by streams and other meltwaters, and the freshwater is dammed behind the ice shelf. Epishelf ecosystems therefore contain the unusual combination of freshwater, brackish, and marine biota in different layers of the same water column.

Freshwater lakes are found in many parts of the continent but particularly in maritime Antarctica where temperatures are warmer and the precipitation much greater. These lakes have more complex food webs than in the continental regions, with copepods (notably *Boeckella poppei*), fairy shrimps *(Branchinecta gaini),* and in some locations such as the abundant lakes on the Byers Peninsula of Livingston Island, a species of insect (the dipteran *Parochlus steinenii*). The large (up to 7.5 mm at Signy Island) predatory copepod *Parabroteas sarsi* is also known from some maritime antarctic lakes. Moss and green algae, in addition to cyanobacteria, are found growing profusely on the bottom of freshwater lakes at several locations, including Yukidori Lake in the Langhovde region of the continent (where *Leptobryum* sp. forms curious underwater "moss towers") and Signy Island lakes in maritime Antarctica. Long term measurements at Signy Island have shown a clear warming trend in the lakes, and evidence of the effects of changing ice cover on plankton dynamics.

A variety of extreme ice-dependent lakes and pools are found throughout Antarctica. Meltholes called cryoconite ("cold rock dust") holes, first described and named on the Greenland ice cap, form in the glacier ice, fill with water, and provide a habitat for cyanobacteria and other biota. These microecosystems are typically initiated by local heating of sediments on the glacier surface. Larger meltwater pools form in shallow perennial basins in the ablation zone of certain ice shelves, notably the McMurdo Ice Shelf. These contain red, brown, or orange mats of cyanobacteria up to several cm thick, with a variety of other microbes including heterotrophic bacteria, protists and microinvertebrates such as rotifers and nematodes. One common rotifer species, *Philodina gregaria,* forms conspicuous bright-red clusters of animals on the surface of the mats and was first described by James Murray in his work on Ross Island algal mats during Shackleton's expedition.

Some of the most intriguing lakes in Antarctica have yet to be sampled. Geophysical surveys have shown that more than 140 water bodies occur deep beneath the Antarctic ice cap where the geothermal heat flux in combination with latent heat and the insulating effect of the ice cover allows liquid water to persist throughout the year. The largest of these is Lake Vostok which has a surface area of 14,000 km^2, lies beneath 3700–4300 m of ice, and has a maximum liquid water depth of 800 m. Analyses of deep, lake-derived ice has provided indirect evidence of an active microbial community in Lake Vostok, but the physical, chemical, and biological properties of this and other subglacial Antarctic lakes currently remain an enticing mystery.

WARWICK F. VINCENT

See also **Algal Mats; Antarctic Ice Sheet: Definitions and Description; Biogeography; British Antarctic *(Nimrod)* Expedition (1907–1909); Cryoconite Communities; Dry Valleys; Food Web, Marine; Lake Vostok; Microbiology; Oases; Ross Island; South Orkney Islands; South Shetland Islands; Subglacial Lakes; Temperature**

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SUB-ANTARCTIC FUR SEAL

The sub-Antarctic fur seal *(Arctocephalus tropicalis)* is one of the two species of otariid ("eared" seals) that are found in the Antarctic regions. The other is the Antarctic fur seal *(A. gazella)*. Both species occur in the Prince Edward Islands, where they can be distinguished by the fact that sub-Antarctic fur seals are smaller, tend to be paler, and have shorter, broader foreflippers. Interbreeding between the two has been described both at the Prince Edward Islands and on Macquarie Island, so hybrids can occur. Taxonomists have argued for years about the relationship between these two species (and between these two and the other species of the genus *Arctocephalus*), although the debate is soon likely to be resolved by DNA analysis.

Like all members of the genus *Arctocephalus,* sub-Antarctic fur seals are characterised by their thick fur, a feature that allows them to keep warm in relatively hostile environments but that also made them attractive to humans, who have traditionally killed them for their rich pelts. Males average an approximate weight of 88–130 kg, and females 34–36 kg. They are compact in appearance, with short, thick necks and short, broad foreflippers. Adults of both sexes are dark grey-brown with pale, gingery chests and faces. The whiskers are long and white. Males have a tuft of guard hairs on the head that forms a distinctive crest, or topknot, which can appear larger when the animal is agitated.

These fur seals breed at a number of subtemperate islands of the Indian, South Atlantic, and South Pacific oceans. Most populations are increasing gradually now that they are not being hunted, although their remote locations mean that it is difficult to estimate the total population with any accuracy.

In the Tristan da Cunha Island group, the breeding population is greatest on Gough Island, although smaller colonies also occur on Inaccessible and Nightingale islands. Sealers arrived in the late eighteenth century, and were so thorough that by the 1830s they were complaining that there were too few animals left to make for an economically viable season. Once left alone, however, the population recovered well, and Gough Island now boasts the largest sub-Antarctic fur seal population in the world.

A smaller breeding colony is centred in the Prince Edward Islands, mostly on Marion Island. Because the fur seals here were never very abundant, they were not hunted as rigorously as some of the other populations, and in the 1970s their numbers were estimated to be just below 10,000 animals. They tend to inhabit the rocky coasts on the west side of the islands.

Îles Crozet also had a small population, but this was virtually exterminated by hunters in the nineteenth century, and although recolonisation has occurred, it has not done so at the same rate as Gough.

The population at Île St. Paul and Île Amsterdam, sometimes called the Amsterdam Island fur seal, has recovered from intensive culling and the islands now have thriving colonies. Finally, a small population has been recorded on Macquarie Island, where it can be confused with the New Zealand fur seal *(A. forsteri)*. The sub-Antarctic fur seal is a wide-ranging species, and stragglers have been recorded as far afield as Brazil, South Georgia, South Africa, and southern New Zealand.

In terms of reproduction, adult males arrive at the breeding grounds in September and begin to stake out their territory. In the following months, the juveniles and females arrive, the younger males keeping well away from the beaches occupied by the dominant bulls. Pups are born between November and February, depending on location, usually within a few days of the cows' making landfall. The black or dark brown pups are about 60–65 cm long at birth and weigh 4–5 kg. Mating takes place 8–12 days after the birth of the pups, after which the females begin to make short feeding trips to sea. Pups of this species suckle for almost a year, probably until the next pup is born.

Sub-Antarctic fur seals are generalised feeders, and will take squid, fish, and krill. On Île Amsterdam, they have also been observed eating rockhopper penguins. In turn, they are predated upon by killer whales and sharks.

LIZ CRUWYS

See also **Amsterdam Island (Île Amsterdam); Antarctic Fur Seal; Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Convention on the Conservation of Antarctic Seals (CCAS); Crozet Islands (Îles Crozet); Crested Penguins; Fish: Overview; Gough Island; Killer Whale; Macquarie Island; Prince Edward Islands; St. Paul Island (Île St. Paul); Squid; Zooplankton and Krill**

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SUB-ANTARCTIC ISLANDS, GEOLOGY OF

This article describes the geology of those oceanic islands in the Southern Ocean that are not described in other specific entries. Many of the sub-Antarctic islands have been visited only rarely and knowledge of them, especially of their geology, is extremely limited.

Balleny Islands

The Balleny Islands (66°15′ to 67°35′ S, 162°30′ to 165°00′ E) comprise three main islands, Young, Buckle, and Sturge islands, extending for about 160 km in a southeast–northwest direction about 350–450 km north of the Oates Coast of northern Victoria Land. They cover an area of about 400 km^2, reach a maximum height of 1524 m on Sturge Island, and are about 95% glaciated.

The islands are entirely volcanic and comprise interbedded tuff, agglomeratic scoria, and lava flows. Compositions of rock specimens examined include trachybasalt, basalt, and hawaiite. No radiometric age determinations have been made, but the rocks are probably of late Cenozoic age, and a maximum age of 10 Ma may be inferred from seafloor magnetic patterns. Seafloor sediments in the south Pacific Ocean, deposited during the past 2.5 Ma, contain windblown rhyolitic volcanic dust that is considered to have been derived from violent eruptions in the Balleny Islands. In 1839 and 1899, mariners described Buckle Island in eruption, but an infrared survey of the islands in 1967 failed to define any thermal anomalies. Some of the small islands may be volcanic plugs or necks.

Bouvetøya

Bouvetøya (54°25′ S, 03°22′ E) is the remotest island on the planet, being about 1700 km from the nearest other land, the Prinsesse Astrid Kyst of Dronning Maud Land. It covers an area of about 54 km^2, rising to 935 m at Olavtoppen, and is about 93% glaciated. Larsøya is an islet lying off the southwest coast.

Bouvetøya lies on the Mid-Atlantic Ridge where it turns eastward and separates the African Plate from the Antarctic Plate. It forms a volcanic cone of basalt with a prominent central crater. Radiometric dating of the lavas have shown the oldest to be 1.3 Ma, and the youngest to be 0.1 Ma. The volcano is still active, as indicated by the presence of fumaroles. At some time between 1955 and 1958 a relatively flat platform was formed extending from the western side of the island south of Kapp Circoncision, probably as a result of volcanic activity and localized tectonic uplift. This area, Westwindstranda, is about 1500 m long and up to 300 m wide.

The island is entirely volcanic and the lavas belong to the alkali-basalt–trachyte–rhyolite series. Specimens of basalt, rhyolite, and obsidian have been recorded together with pumice and tuffaceous strata and rare trachyte lavas from the recently formed platform. Numerous dykes have also been recorded along the west coast. The summit of the island is a flattish, circular crater about 2 km in diameter that is assumed to have been the source of the eruptions that provided the main bulk of the island.

In 1825, George Norris commanding the sealing vessel *Sprightly,* reported sighting "Thompson Island" about 72 km north-northeast of Bouvetøya and described it as volcanic. The island was sighted again in 1893 by Joseph Fuller, commanding the sealing vessel *Francis Allyn*. This island has never been seen since then and has been described, with early sightings of other islands, as "nonexistent." However, more recent research has suggested that the island did exist and that it probably disappeared in a volcanic eruption in 1895 or 1896.

Heard Island

Heard Island (53°05′ S, 73°33′ E) and Shag Island about 11 km to the north cover an area of about

385 km^2. Mawson Peak rises to 2745 m, and the island is about 80% glaciated.

Heard Island is dominated by the central volcano of Big Ben. The oldest rocks are the marine limestones of Lower Tertiary age that crop out on Laurens Peninsula and Rogers Peninsula in the northwest and at some other points along the north coast. These are intruded by trachy-basalt intrusions, a composition not found in the later volcanic sequences. A period of erosion followed with the deposition of glacial sediments and the eruption of submarine lavas in Late Tertiary or early Pleistocene times. Above these are the lava formations that constitute the main edifice of the island. There are some younger lavas around the coast, probably from subsidiary vents on the main volcano, but the main bulk of Big Ben was probably formed by eruptions during the Pleistocene. There are also younger volcanic rocks in the cone of Mawson Peak.

Macquarie Island

Macquarie Island (54°37′ S, 158°58′ E) covers an area of 128 km^2 and rises to 433 m on Mount Hamilton. Judge and Clerk Islands lie about 16 km to the north, and Bishop and Clerk Islands lie about 29 km to the south. The islands are not glaciated.

Macquarie Island lies on the Macquarie Ridge Complex and represents a section of the ocean floor formed by sea-floor spreading processes, possibly about 27 Ma, that has been uplifted over the past 10 Ma by plate tectonic processes between the Indian and Pacific–Australian plates. The island has been above sea level for about 0.7 Ma and continues to rise at about 0.8 mm per year. The island's morphology is due to uplift, erosion, and sea level changes giving rise to raised beaches that indicate the island has never been glaciated.

In the southern two-thirds of the island, the bedrock geology comprises basalt pillow lavas, with pockets of *Globigerina* ooze between the pillows, and volcanic breccias. In the northern third of the island an ophiolite complex is exposed, comprising serpentinized peridotite, gabbro, layered gabbro, and pillow lava. Dolerite dykes are common, including some areas of sheeted dolerites in the north.

Peter I Øy

Peter I Øy (68°51′ S, 90°37′ W) covers an area of about 157 km^2 and rises to 1640 m on Lars Christensentoppen. The island is about 95% glaciated.

The island is the exposed top of a volcanic edifice rising 4000 m from the sea floor, close to the oceanic–continental crust transition and close to a former transform fault in the Tharp fracture zone. The rocks are predominantly alkali basalt and hawaiite lavas, probably all extruded during the last 0.5 Ma. Older ages of 12.5 Ma suggest that the original formation of the volcano began some 10–20 Ma.

Scott Island

Scott Island (67°24′ S, 179°55′ W) covers an area of about 0.1 km^2 and rises to 39 m. Haggits Pillar lies off-shore to the west and is 63 m high. The island is about 80% glaciated.

The island is volcanic but the only known rock specimen from the island (collected in 1902 during the *Morning* expedition) is a phonolite that is considered to be of Cenozoic age. Dredge specimens from the vicinity of the island are also phonolite.

Peter Clarkson

See also **Balleny Islands; Bouvetøya; Heard Island and McDonald Islands; Macquarie Island; Peter I Øy; Plate Tectonics; Southern Ocean; Volcanoes**

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SUB-ANTARCTIC SKUA

Sub-Antarctic skuas (*Catharacta* ssp., members of the family Stercorariidae, Charadriiformes) inhabit coastlines and islands in the Southern Ocean between the austral part of South America and New Zealand. They share the brown plumage and white wing patches with other *Catharacta* species but are of larger size, prey mainly on seabirds, and show less expanding migratory behaviour (compare South Polar skua; see also skua overview for general characteristics). Sub-Antarctic skuas breed in loose colonies in close vicinity to other seabird nesting sites, incubate a clutch with normally two eggs (inexperienced birds lay one egg) for 28–32 days, and defend their chicks until fledging at an age of c. 50 days. In the following weeks, breeding sites are abandoned, and in springtime partners meet again in the same territory to reproduce.

Sub-Antarctic skuas are divided in the three subspecies brown skua *C. a. lonnbergi,* Falkland skua *C. a. antarctica,* and Tristan skua *C. a. hamiltoni* (an alternative classification nominates *C. antarctica spp.* as brown skuas and *C. a. lonnbergi* as Sub-Antarctic skua). Hybridisation is known for brown and South Polar skua and with Falkland and Chilean skuas.

Brown skuas are the largest and most widespread of the three forms, showing increasing measurements from the Antarctic Peninsula, on the peri-Antarctic islands towards New Zealand (total 7000–10,000 pairs). The plumage can vary from dark to light brown with irregular pale streaking on the upper parts. Brown skuas show the widest food spectrum partly holding feeding territories. Many feed in penguin colonies on eggs, chicks, and adults. Some also specialise in hunting burrowing petrels on land or seal carcasses and placentae at sea. To a lesser extent, they follow fishing boats and use human food waste in Antarctic research stations.

The smallest subspecies, the Falkland skua (local name: sea hen) breeds on the Falkland Islands and the coasts along southern Argentina with a population of 3000–5000 pairs. They can be recognised by a marked dark cap lacking any rusty body colouring that would suggest a Chilean skua. Falkland skuas feed in penguin, petrel, and cormorant colonies. Adults and juveniles disperse northwards up the coast of South America for the winter.

The third subspecies has its name from the remotest inhabited island in the world—Tristan da Cunha. Due to high human persecution in the past, the Tristan skua population is currently about 200 pairs on the archipelago. Additionally, this form can be found in higher numbers (c. 2300 pairs) on uninhabited Gough Island that lies some 320 km southwest of Tristan. This skua form appears more uniformly dark with less white streaking, and although slightly smaller than brown skuas, bill and legs are proportionally longer. They prey on penguins, burrowing petrels, and small mammals. Outside the breeding season, Tristan skuas usually remain close to their nesting areas.

Simone Pfeiffer

See also **Antarctic Peninsula; Chilean Skua; Skuas: Overview; South Polar Skua**

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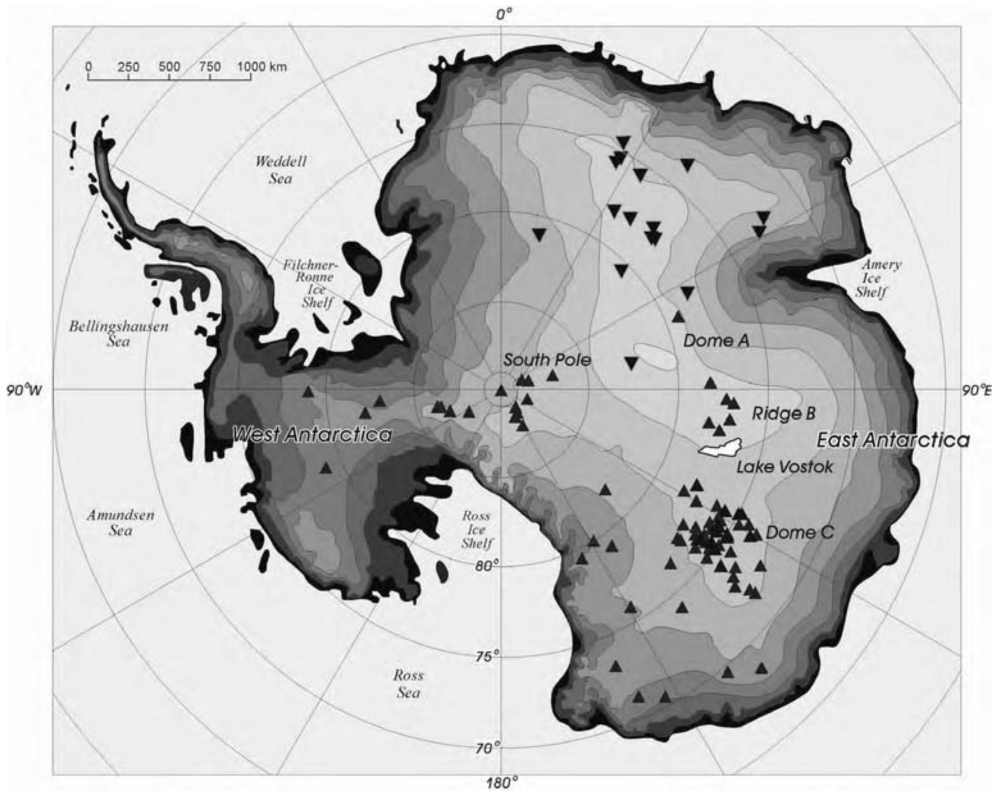
SUBGLACIAL LAKES

Subglacial lakes are bodies of liquid water that exist at the base of large ice sheets. They occur as a consequence of geothermal heating from the Earth, the insulating effect of the overriding ice, and the pressure of the ice overburden, which collectively allow the ice temperature to reach around –3°C, whereupon it melts. Meltwater flows under gravity and the pressure of ice, and collects in topographic hollows to form lakes.

Subglacial lakes were discovered in the late 1960s using a technique called radio-echo sounding. Radio waves travel well in cold ice but reflect off boundaries where there is a contrast in electrical properties. Reflections off the ice-rock interface are very different than those from the ice-water surface of a subglacial lake, which are stronger and flatter. The first inventory of subglacial lakes, published in 1996, identified over seventy lake-type surfaces. Since then, thirty new lakes have been identified, bringing the total up to one hundred.



Distribution of Antarctic subglacial lakes.

The largest subglacial lake, by an order of magnitude, is Lake Vostok, which is 250 km long. The next largest is Lake Concordia, which is over 30 km in length. Several other subglacial lakes have dimensions in excess of 10 km in length. In contrast, however, the bulk of Antarctic subglacial lakes are between 3 and 5 km long. Subglacial lakes in excess of 5 km in length manifest themselves as flat regions on the ice surface, and are detectable from satellite altimetry. These flat regions allow the aerial extent of large subglacial lakes to be mapped approximately.

Radar represents an excellent means by which subglacial lake surfaces can be identified, but as radio waves do not penetrate well in water it cannot be used to determine information on the depth of subglacial lakes if they are deeper than a few metres. Seismic sounding is the only feasible way of gaining information about the water depths of subglacial lakes from the ice surface. Very few seismic experiments have been undertaken over subglacial lakes, however. The gradient of side-wall slopes bordering lakes provides an indication of the water depth to be expected in many cases. This has often shown the water depths of subglacial lakes likely to be several tens if not hundreds of metres. Analysis of side-wall slopes allows the total volume of water stored beneath the Antarctic ice sheet to be estimated between 7000 and 15,000 km^3.

Subglacial lakes occur in a variety of topographic and glaciological settings. They can be classified into three distinct groups: (1) lakes in subglacial basins in the ice-sheet interior, (2) lakes perched on the flanks of sub-glacial mountains, and (3) lakes close to the onset of enhanced ice flow. The majority of subglacial lakes are located within 200 km of ice divides of both the East and West Antarctic ice sheets. The bedrock topography of the ice-sheet interior involves large subglacial basins separated by mountain ranges. Subglacial lakes in the first category are found mostly in and on the margins of subglacial basins. These lakes can be divided into two subgroups. First, there are those located where subglacial topography is relatively subdued, often towards the centre of subglacial basins. Second, some lakes occur in significant topographic depressions, often closer to subglacial basin margins, but still near the slow-flowing centre of the Antarctic Ice Sheet. Where bed topography is very subdued, deep subglacial lakes are unlikely to develop. Lake Vostok is the only subglacial lake that occupies a whole section of a large subglacial trough. Other troughs, such as the Adventure Subglacial Basin contain a number of smaller lakes. “Perched” subglacial lakes are found mainly in the interior of the ice sheet, on the flanks of subglacial mountain ranges. In several cases, small (<10 km long) subglacial lakes have been observed perched on the stoss face of large (>300 m high), steep (gradient > 0.1) subglacial hills. At least sixteen subglacial lakes occur at locations close to the onset of enhanced ice flow, some hundreds of kilometres from the ice-sheet crest. The highest density of known subglacial lakes occurs in the Dome C region of East Antarctica, where more than forty have been identified. Some of these lakes are so close that they may be connected hydrologically within the same watershed.

Many subglacial lakes have been shown to have ceilings that slope at ten times the ice surface slope (but in the opposite direction). This condition is achieved under hydrostatic equilibrium and suggests that lakes are stable features, in balance with the ice sheet above and topography beneath. Perturbations to this balance are likely to occur over glacial-interglacial cycles, because the thickness and surface elevation of the ice sheet is expected to change. Such change, even if slight, will cause a response ten times as great at the ice water interface (for the lake to remain in hydrostatic equilibrium) and, consequently, we may expect subglacial lake size to be affected over periods of 100,000 years.

Water circulation processes are likely in subglacial lakes and will be driven by the slope of the ice-water interface. The slope of a lake's ceiling results in differential rates of melting, which is likely to induce mixing and circulation of water. Ice that melts into subglacial lakes will supply impurities to the lake, such as gases, dust, and rock flour. Conversely, lake water frozen to the underside of the ice sheet, as has been recovered by the Vostok ice core, contains little other than pure ice. Thus, there is likely to be a buildup of material within subglacial lakes over time. This has led some to believe that the subglacial lake waters may be enriched in dissolved gases and, if this is the case, gas hydrates (crystal lattices formed by water molecules around gas molecules under conditions of low temperatures and high pressures, often called "clathrates").

The age of a subglacial lake is dependent on two factors. The first is the date at which the ice sheet most recently allowed the lake to exist. For many lakes of the order of several tens of metres deep in East Antarctica, this date could be as old as 15 Ma, as some believe the ice sheet has been stable for this length of time. However, some shallow lakes may not survive glacial cycles because of ice sheet flow change and colder ice temperatures. Further, the ice sheet in West Antarctica is thought to have changed significantly during the last 2 million years. Hence, lakes here are likely to be younger than in East Antarctica. The second factor relates to the age of the lake water, which is controlled by the age of the basal ice melt. In East Antarctica this may be upwards of 1 million years. In West Antarctica, on the other hand, the age of the basal ice is likely to be no older than 150,000 years. Consequently, subglacial lakes in West Antarctica will be younger than their East Antarctic counterparts.

There has been a huge degree of scientific and media interest in subglacial lakes, following the discovery 10 years ago that subglacial lakes, and Lake Vostok in particular, were deep. Discussion about whether to make *in situ* measurements of the lake has been driven by two scientific hypotheses. The first is that unique microorganisms inhabit subglacial lakes. The second is that a complete record of ice sheet history is available from the sediments that lie across lake floors. Future exploration of subglacial lakes will be focussed on testing these hypotheses. If the hypotheses are correct future investigations of subglacial lakes could enable valuable insights into the history of Antarctica, detailing its response to and control on climate change, and our understanding of biological functioning within extreme environments.

The Scientific Committee on Antarctic Research, the international body that oversees Antarctic science, commissioned a Subglacial Antarctic Lake Exploration (SALE) "group of specialists" to "consider and recommend mechanisms for the international coordination of a subglacial lake exploration program." The techniques necessary for the exploration of subglacial lakes depend on the hypothesis to be tested. Testing whether microbes live in the lake requires totally sterile equipment, which must be miniaturised to fit within an ice borehole. It seems unlikely that the traditional ice core boreholes can be used for this purpose, as they are filled with a drilling fluid that contains impurities that need to be excluded from the lake. Hot water drilling appears to be the only feasible means of boring down to a subglacial lake without risking contamination, but no hot water drill has ever penetrated through in excess of 3 km of ice above most subglacial lakes. There are, consequently, substantial technological hurdles to overcome in order to set up an appropriate experiment to find life in subglacial lakes. Testing whether climate records exist in sediments on the lake floor does not require contamination controls. There is strong opinion, however, that lake environments should not be polluted. This will almost certainly mean that geological investigation of the lake is undertaken with contamination controls, which is likely to increase the cost of such work hugely.

Although the scientific rational for subglacial lake exploration is well defined, the identification of the first lake target is less clear. Some argue that Lake Vostok is the most appropriate site. Others argue its huge size makes it difficult to comprehend in a detailed manner, and that access technologies should be tested on other less ancient lakes first. This makes the exploration of West Antarctic subglacial lakes particularly appealing for exploration in the first instance.

MARTIN J. SIEGERT

See also **Air Hydrates in Ice; Antarctic Ice Sheet: Definitions and Description; CryoSat; Geological Evolution and Structure of Antarctica; Glacial Geology; Glaciers and Ice Streams; Ice–Rock Interface; Ice Sheet Mass Balance; Ice Sheet Modeling; ICESat; Lake Ellsworth; Lake Vostok; Surface Features**

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SURFACE ENERGY BALANCE

The surface energy balance (SEB) describes the partitioning of energy fluxes towards and away from the surface (unit: W m^{-2}). For an infinitesimally thin surface layer without heat capacity, these fluxes *balance* (i.e., their sum equals zero). The local SEB is of extreme importance for it determines the temperature of the Earth's surface. When the surface consists of snow or ice, the SEB also determines the amount of energy that is available for sublimation and melting. These processes directly couple the SEB to the *surface mass balance* (see entry elsewhere). The major components of the SEB are

- *Net radiation,* consisting of four components: *incoming and reflected shortwave (solar) radiation* and *incoming and upwelling longwave (terrestrial) radiation*. These two radiation types are distinguished on the basis of their wavelength, determined by the temperature of the body that emits the radiation through Stefan-Boltzmann's law. If radiation originates from the surface of the Sun ($T \approx 5800$ K), either directly or scattered in the Earth's atmosphere, nearly all energy is confined in wavelengths below 5 micrometer, hence the name *shortwave radiation*. Note that visible light is shortwave radiation but that not all shortwave radiation is visible light. If the radiation originates from the Earth-atmosphere system ($T \approx 200$–300 K), nearly all energy derives from wavelengths greater than 5 micrometer, hence the name *longwave radiation*.
- *Turbulent heat fluxes,* consisting of the *sensible* and the *latent* heat flux. The sensible heat flux describes heat exchange between the surface and the air just above it. This flux is directed towards the surface when the air is warmer than the surface and vice versa. The latent heat flux equals the amount of heat extracted from or added to the surface as a result of sublimation (the phase change from solid ice to water vapour) or deposition (phase transition from vapour to solid [i.e., rime formation]). Both sensible and latent heat fluxes are *turbulent* heat fluxes (i.e., they arise from the presence of turbulent eddies in the air that mix heat and moisture vertically). For the sensible/latent heat fluxes to be nonzero, turbulence must be present *and* there must be a temperature/moisture difference between the surface and the air.
- *Subsurface heat flux,* representing the conduction of heat into the subsurface strata; this flux is almost entirely driven by molecular conduction (i.e., by vertical temperature gradients in the snow).

The annual mean SEB of a typical midlatitude grass surface has net radiation as the main heat source and turbulent exchange of latent heat (evaporation) followed by sensible heat (convection) as main heat sinks. Judging from the very low temperatures, the Antarctic SEB must be very different. To start with, all energy fluxes are an order of magnitude smaller than at midlatitudes. The incoming longwave radiation flux is relatively small because the Antarctic atmosphere is thin, cold, dry, clear, and clean. The shortwave radiation balance is even more extreme. The downward annual mean shortwave radiation flux through the top of the atmosphere at the pole is only 40%–50% of that at the equator. Of that already reduced amount, only 5%–15% is finally absorbed at the dry and clean snow surface, which is highly reflective for shortwave radiation (i.e., it has a high *albedo*). As a result, net radiation is *negative* in the annual mean, implying that net radiation represents a *heat sink* in the Antarctic SEB. Elsewhere on Earth, this feature is only found in the dry snow zone of the Greenland ice sheet.

The surface heat sink caused by radiation must be balanced by a significant heat source in the other SEB terms. The subsurface heat flux is ruled out as a possible candidate because this would require a continuous cooling of the snow pack. The latent heat flux is no candidate either, for it only deviates significantly from zero only in summer, when sublimation acts as a net heat *sink*. This leaves the sensible heat flux. Two conditions must be met for transport of sensible heat to the surface to occur: first, the air must be warmer than the surface. Measured temperature profiles indicate that a surface based temperature inversion (i.e., temperature increasing with height) indeed is a common feature of the lower Antarctic atmosphere (see entry on the Atmospheric Boundary Layer). Second, strong near surface winds are required to generate the turbulence needed to effectively transport heat towards the surface. This condition is fulfilled by the notorious Antarctic katabatic winds, forced by gravity acting on the cold, negatively buoyant near-surface air (see entry on katabatic winds). A significant surface slope is a prerequisite for katabatic winds to develop; for flat areas, such as the coastal ice shelves and the interior plateau, katabatic winds will be weak or absent. As a result, sensible heat gain and radiative heat loss are considerably smaller at these sites.

The fact that the subsurface and latent heat fluxes are not dominant in the seasonal cycle does not mean that they are unimportant components of the Antarctic SEB. On time scales of several hours, the sub surface heat flux is the main SEB component to balance rapid changes in the radiation balance when turbulence is weak. During summer the latent heat flux becomes the major heat sink at daytime. A latent heat flux of –10 W m^{-2} (the negative sign indicating energy removal from the surface) suffices to sublimate over 9 kg of snow per square meter per month. Especially in dry areas, this constitutes a significant component in the surface mass balance.

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See also **Antarctic Ice Sheet: Definitions and Description; Firn Compaction; Ice–Atmosphere Interaction and Near-Surface Processes; Ice Sheet Mass Balance; Precipitation; Snow Biogenic Processes; Snow Chemistry; Snow Post-Depositional Processes; Surface Mass Balance**

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SURFACE FEATURES

The Antarctic continent is essentially circular in shape, except for the flaring Antarctic Peninsula and for two principal embayments (Ross Sea and Weddell Sea). The continent is divided by the Transantarctic Mountains into two distinct regions: West, or Lesser, and East, or Greater, Antarctica. At some locations around Antarctica, ice flowing from the grounded portion of ice sheet forms large floating ice shelves, which account for about 10% of the total continental ice area. The three largest ice shelves are the Ross and the Ronne-Filchner ice shelves in West Antarctica and the Amery Ice Shelf in East Antarctica. The surface extension of contiguous continent is about 12 million km^2. The bulk of the continent's ice is contained in the Greater Antarctic (9.86 million km^2). The highest point of the East Antarctic Ice Sheet is Dome Argus (77° E, 81° S); it reaches a maximum height of 4078 m and it is situated above the subglacial Gamburstev Mountain (about 3000 m above sea level), whereas the highest rocky peak on the continent is the Vinson Massif (82°25′ W, 78°35′ S), which rises to an altitude of 4897 m, and is situated in the Ellsworth Mountain Range. West Antarctica (2.23 million km^2) is smaller and lower in elevation than East Antarctica. Antarctica presents an average elevation of 2500 m, and it is the highest and flattest continent on Earth (about 70% of surface presents slope less than 4 m/km). This enormous mantle of ice is piled onto a rocky substratum that extends for large stretches below sea level. The average thickness of ice layer is around 2160 m, though extensive areas can reach down over 4000 m in the Bentley Valley (110° W, 81° S), in West Antarctica, as well as in East Antarctica at Aurora (120° E, 74° S) and Astrolabe Basin (135°12′ E, 69°54′ S), where it reaches its maximum thickness (4776 m) in the latter zone.

The Antarctic continent is almost completely covered with snow; only 0.3% of its surface is exposed rock/sediment, and 1% is blue ice. Exposed rock/sediment is found in the Transantarctic Mountains, on the Antarctic Peninsula, and in some coastal areas. Blue ice areas are scattered widely over the continent, mainly in the vicinity of nunataks and mountain range and close to the coast in katabatic wind confluence zone. Many types of surface microrelief and macromorphology, such as at metre scale sastrugi, snow dunes, barchane, wind crust and pitted patterns and at kilometre scale megadune, longitudinal and transverse dune, are distributed on the surface of the Antarctic ice sheet in various sizes (from decimetre to kilometre) and occur as a result of interactions between the air and the ice sheet surface.

An ice divide longer than 5000 km crosses the inner part of East Antarctica from the Atlantic to Pacific Ocean and summits in four domes (Dome Fuji or Valkyrie, Dome Argus, Dome B, and Dome Circe or Charlie). West Antarctica consists of an archipelago of mountainous islands covered and bonded together by ice, without any well-formed dome shape. A dome is a rounded and gently sloping elevation in the surface of an inland ice sheet; it does not have precisely defined margins and may cover very large areas (more than 100,000 km^2). An ice divide defines the inner margins of ice drainage basins and may be defined as the plane extending from the base to surface, through which there is no transport of mass. Thus, an ice divide separates ice flowing in opposite directions. The divide plane (the plane from the surface to bedrock that separates ice flowing in opposite directions) may present a slope such that the ice divide at the ice-bedrock interface does not directly underlay the ice divide at the surface. The different location of ice divide at surface and at bedrock could be due to the asymmetric conditions in basal topography and snow accumulation across the highest point of ice sheet. The movement of the ice spreads down radially from the domes, and ice divides towards the coast. The ice speed varies from a few centimetres per year close to domes and ice divides to hundreds of meters per year in fast-flowing rivers of ice, known as ice streams. About 90% of the ice discharge from the interior to the ice margin is drained through a small number of ice streams and outlet glaciers. These penetrate up to 1000 km from the grounding line into the interior of the ice sheet by complex tributary systems. Outlet glaciers and ice streams fill troughs and could reach incredible dimensions. For example, the Lambert Glacier-Amery Ice Shelf basin (about 1.32 million km^2) is over 700 km long and occupies the widest trough on earth.

The shape of an ice sheet is mainly convex and is primarily determined by the changing properties of ice, ice thickness, ice temperature, bedrock condition, accumulation, and ablation rate. The shape is in turn modified by the ice flow, which usually tends to adjust to reach a balance between the mass input (snow accumulation) and output (ablation). Bedrock topography cause irregularities in the ice surface in the inland, and near the coast much of the flow is channelled either by mountain or by deformable sediments beneath the ice. Peculiar surface areas are the regions' overlying subglacial lakes (mainly in the East Antarctica); the absence of friction contact between ice and water at the ice sheet base above the subglacial lake provides itself evidence as an anomalous near-flat region on the ice-sheet surface.

Grounding/floating migration induced by sea level changes is the primary factor governing the temporal evolution of the Antarctic ice volume and morphology. However, when considering the topography of the East Antarctic Plateau the influence of grounding line migration is weak, and ice divide location and elevation appear to be complex functions of spatial and temporal variations in the snow accumulation rate. Ice sheet models revealed that surface elevation at the dome varied by up to 100–150 m whereas the lower portion of ice sheet close to the coast thickened up to 1000 m between glacial and interglacial period.

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See also **Antarctic Ice Sheet: Definitions and Description; Firn Compaction; Ice–Atmosphere Interaction and Near-Surface Processes; Mega-Dunes; Snow Biogenic Processes; Snow Chemistry; Snow Post-Depositional Processes; Surface Energy Balance**

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SURFACE MASS BALANCE

The surface mass balance is defined as the annual sum of solid mass fluxes directed towards and away from the surface (unit: kg m^{-2} year). These mass fluxes usually do not balance so that one frequently encounters the somewhat strange expressions *positive surface mass balance* (or *accumulation*) and *negative surface mass balance* (or *ablation*). In the absence of a well-defined ablation zone, Antarctica is usually regarded as one big accumulation area. When summed over the grounded ice sheet, the surface mass balance constitutes the largest positive contribution to the *ice sheet mass balance*. Only about 1% of the Antarctic surface consists of *blue ice areas,* where the surface mass balance is negative. They owe their name to the milky-blue appearance of old glacier ice that surfaces when the 70–100 m thick snow and firn layer has been removed by snowdrift erosion and/or sublimation. Because of the local upward ice movement, blue ice areas are major meteorite collection sites. The components of the Antarctic surface mass balance are

- *Solid precipitation* (snowfall) is by far the biggest positive component of the surface mass balance in Antarctica. Precipitation in Antarctica consists mainly of snowfall from frontal clouds, with topographic effects playing a very important role. It has been suggested that in the high interior a substantial part of the solid precipitation flux falls as "clearsky precipitation" or "diamond dust," ice crystals that form when near surface air cools and becomes saturated. The ice crystals do not noticeably affect visibility but are often accompanied by spectacular optical phenomena.

- *Surface sublimation* is the largest negative term in the surface mass balance of Antarctica. Current estimates show that sublimation removes about 7% of the solid precipitation but with large regional and temporal differences. Sublimation can be very important for the regional mass balance and is believed to be responsible for the formation of blue ice areas on large outlet glaciers, where adiabatic heating and drying of the air may cause considerable latent heat fluxes.
- *Melt* is generally confined to the low-lying parts of the ice sheet and ice shelves. Nearly everywhere in Antarctica, meltwater that is formed at the surface and penetrates the snow pack, refreezes at some depth, where temperatures are generally still below zero (internal accumulation). Exceptions are the ice shelves in the northern Antarctic Peninsula, where extensive meltwater lakes are detected on satellite imagery. This collection of meltwater at the surface has been linked to the recent disintegration of some of these ice shelves.
- *Snowdrift,* snow blown by the wind, can cause significant variability in snow accumulation from place to place, even between closely spaced sites. It affects the surface mass balance in two ways. *Snowdrift sublimation,* the sublimation of suspended snow particles, is a potentially important process because a suspended snow particle has a maximally exposed surface. However, the sublimation process is so effective that after its onset the surrounding air quickly becomes saturated, halting further sublimation. *Horizontal gradients in drifting snow transport* cause erosion or deposition at the surface. For the Antarctic surface mass balance as a whole this process is probably unimportant, but in the vicinity of topographic obstacles this process may be locally important. More snowdrift experiments and better models are needed in order to quantify the potentially important influence of snowdrift processes on the Antarctic surface mass balance.

The surface mass balance can be rather easily measured using stakes, snow pits, and snow cores. The latter two methods are only applicable in accumulation areas and use well-known dating horizons such as volcanic eruptions, providing the average mass balance for a known time interval. For a better temporal resolution, a sonic height ranger mounted on an Automatic Weather Station can be used. If all mass balance observations are painstakingly collected, quality controlled, interpolated, and mapped, a new *mass balance compilation* of Antarctica is born (e.g., Vaughan 1999). A background interpolation field is often used for data sparse regions, commonly provided by remotely sensed characteristics of the upper snow layers.

The individual mass balance components are not easily measured. Precipitating snow, for instance, cannot be distinguished from drifting snow, and classical precipitation gauges do not work well in Antarctica. Fortunately, mass balance simulations using regional atmospheric models nowadays compare favorably with compiled observations. The big advantages of a modeling approach are the complete spatial and temporal coverage and the ability to study the individual mass balance components. There is a very strong topographical effect on the precipitation distribution: the coastal, predominantly easterly circulation produces pronounced precipitation shadows west of topographic obstacles in coastal East Antarctica. The northern Antarctic Peninsula, situated in the subpolar westerly circulation, casts a precipitation shadow that reaches all the way east to coastal Dronning Maud Land.

Sublimation is largest at the foot of the ice sheet, where the relative humidity is low and temperatures are relatively high due to adiabatic compression of the descending air. The combination of low precipitation and strong sublimation may result in areas with a negative mass balance. This occurs on a large scale in the Lambert Glacier basin, at the foot of the Transantarctic Mountains, and in Victoria Land. These areas are known for their extensive blue ice fields. Melting occurs mainly on the coastal ice shelves and becomes especially large in the northern Antarctic Peninsula; here, melting exceeds solid precipitation, which also leads to a negative mass balance. These areas have seen rapid disintegration of ice shelves as a result of meltwater collection in crevasses.

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See also **Air-Borne Ice; Antarctic Ice Sheet: Definitions and Description; Atmospheric Boundary Layer; Climate; Climate Change; Earth System, Antarctica as Part of; Firn Compaction; Ice–Atmosphere Interaction and Near-Surface Processes; Ice Sheet Mass Balance; Mega-Dunes; Precipitation; Snow Post-Depositional Processes; Surface Energy Balance; Surface Features; Temperature**

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SWEDISH SOUTH POLAR EXPEDITION (1901–1904)

The Swedish South Polar Expedition was not an officially sanctioned expedition. Despite the ambitions of Dr. Otto Nordenskjöld as he departed from Göteborg, Sweden, on October 16, 1901, he was, in fact, leading an underfinanced, private expedition.

Partly inspired by the discussions at the international geographical congresses held in London, in 1895 and 1897, Nordenskjöld began to coordinate his plans for an Antarctic expedition with the geographical societies of Great Britain and Germany. He was working on a number of projects to be carried out in Graham Land on the Antarctic Peninsula, primarily related to climate studies, but geomagnetism also figured prominently, and research programs in geology, biology, zoology, glaciology, and hydrography were also presented. A winter station was planned for the highest latitude possible on the east coast of the Antarctic Peninsula, at Graham Land, and a party aboard the whaler *Antarctic* would work in areas around the Beagle Channel, the Falkland Islands, and South Georgia.

Nordenskjöld managed to raise some private funding, arrange loans, and receive some of the equipment, food supplies, and fuel free of charge, but his request for 35,000 crowns from the Swedish government was rejected. A three-person committee at the Academy of Sciences stated that the expedition was ill-equipped and underfinanced and that the leadership qualities were poor. Nordenskjöld was accused of instigating the extinction of mammals in the Antarctic and his interest in international cooperation was not deemed important, nor were, for that matter, the fields of study proposed for the land party.

Although severely disturbed by the resulting lack of funding from the Swedish government, Nordenskjöld continued his efforts to find provisions and a suitable team of scientists. Reluctantly he leased his vessel during the summer of 1901 to increase his income, and this, along with some necessary repair work, caused the departure of the expedition to be delayed. Yet another setback was the tragic suicide of Third Officer Otto Håkansson, in Göteborg.

Long in advance, Nordenskjöld had contracted the physicist Gösta Bodman, and later he recruited the medical doctor Gunnar Ekelöf and Lieutenant José Maria Sobral, who joined the team following an agreement between Nordenskjöld and the Argentine government. Ole Jonassen was a skilled carpenter also taken on to manage the dogs needed for the sledging, and Gustaf Åkerlundh was chosen to cook.

Johan Gunnar Andersson (geologist) became second-in-command and leader of the ship party. Karl Andreas Andersson (zoologist), Carl Skottsberg (botanist), and Axel Ohlin (zoologist) were all to become members of the ship party, but Ohlin had to leave the expedition due to illness in July 1902. At the very last moment cartographer Samuel Duse was recruited.

Among the first to be hired by Nordenskjöld was Captain Carl A. Larsen, who had a fine reputation due to his two earlier voyages to Antarctic waters. Larsen had been entrusted with the job of finding a crew capable of ice navigation, sealing, and whaling, and he was also given the assignment of obtaining equipment such as harpoons and barrels. Between October 16 and 19, 1901, *Antarctic* was equipped in Sandefjord. Even though no large-scale operations were planned, both sealing and whaling were on the agenda because parts of the salaries, for both the crew and the scientists, depended on the size of catch. Larsen, on his return from Antarctica in 1904, was to continue working with large-scale whaling enterprises for many more years.

Regardless of its private status, Nordenskjöld's expedition had strong moral support as well as other types of backing in Sweden. Professor Gunnar Andersson, not to be confused with second-in-command Johan Gunnar Andersson, acted as liaison between the expedition and influential people in Göteborg and Stockholm, both those funding the expedition and politicians. Economic problems were frequent, and on several occasions Gunnar Andersson had to intervene in order to ensure the continuation of the expedition.

Nordenskjöld himself had seemingly excellent contacts with the Foreign Ministry because just before departure he asked for, and was given, extensive support from the Swedish-Norwegian consuls in the harbours along the way to Antarctica. Favours were also extended from the representatives of the United Kingdoms of Sweden and Norway in Le Havre, London, Buenos Aires, Ushuaia, Port Stanley, and Montevideo. The expedition was favoured with reduced harbour fees, and free or reduced prices for, amongst other things, coal, food supplies, medical services, social visits, and assistance with media relations. Apparently the authorities did have some idea of the potential value of the Swedish South Polar Expedition, either in terms of its scientific or practical merits.

After a stop in Falmouth, *Antarctic* embarked for Buenos Aires. Additional water and coal supplies were arranged in St Vincent, Cape Verde Islands, on November 14–15, and one month later the expedition anchored on the roadstead of Buenos Aires, where the North American artist Frank William Stokes and Lieutenant Sobral joined the expedition. On December 20, the ship proceeded towards Port Stanley, Falkland Islands, with the mission of finding more dogs to add to those brought from Scandinavia, and on December 30, the expedition departed for Staten Island in order to visit an Argentine meteorological station to coordinate the measurement instruments. There had, however, been a lack of sufficient preparation, and after only a few hours' stopover, on January 5, 1902, *Antarctic* headed for the South Shetland Islands.

Although the weather had been favourable, Nordenskjöld commented on the snow and ice conditions upon arrival at Nelson Island, on January 10. During the week that followed several crew members were occupied with sealing, while the scientists trawled for zoological purposes but also to gather water-depth measurements. The expedition, after passing Astrolabe Island and Lois Philippe Island and visiting Paulet Island, reached Cap Seymour on January 16, whereupon Nordenskjöld set up a depot. The ship then proceeded south to find a suitable site for the winter party, but at 66°19′ S it became impossible to pass the heavy ice, and Larsen had to redirect the ship. Even though there was little time left to complete the installation of the winter station, the expedition took a trip into the Weddell Sea. Hydrographical work was carried out, and zoological material was collected from deep layers. Whales were spotted at a distance, and there was time for sealing as well. On February 11, 1902, most of the men went ashore, and on the days that followed a geomagnetic and meteorological laboratory as well as the winter station were erected on Snow Hill, 64°22′ S, 57°00′ W. The ship then set up a depot to assist the sledge tours planned by Nordenskjöld, and on February 21, Larsen and his crew along with the scientific ship party headed for Ushuaia.

At the base, weather observations were made without a break for 20 months, sometimes during harsh conditions: storms, gales, and snow. They discovered that Snow Hill was actually an island, and several minor sledge tours were made as well as two major ones. Sobral and Jonassen accompanied Nordenskjöld on one such trip between September 30 and November 4. Passing Larsen Ice Shelf and facilitating mapping of the eastern peninsula down to 66° S, the winter party engaged in geological studies and collected fossils in the vicinity of the station. In January 1903, they awaited the arrival of the *Antarctic*.

The ship party had returned safely to Ushuaia on March 5, 1902. The Argentine government generously provided both coal and water supplies, but unfortunately the coal had to be reloaded with assistance from prisoners. The ship departed on March 22 for the Falkland Islands, where the artist Stokes now left the ship.

The sealing and its aftermath soon became a major occupation for the crew aboard *Antarctic,* with considerable effects on the scientists. On April 22, the party reached Cumberland Bay on South Georgia, from where the ship departed for the Falkland Islands, where blubber boiling and the reloading of blubber was carried out during the next 4 months. The scientists made excursions and were kept busy with geological, glaciological, hydrographic, and botanical studies along with mapping the region.

On September 15, the ship entered Ushuaia after short stops in Albernal Bay, where Andersson and Ole Wennergard encountered some Ona. Passing Harberton on November 6, the ship left Tekenika and headed for the South Shetland Islands once again. The first and foremost task was to fetch Nordenskjöld and his men, and the second one was to map the western coast of Graham Land and the offshore islands along with the surrounding waters, as far south as to 64°30′ S. The ship party established that there was no strait through the peninsula as indicated on earlier maps. Mapping and the collecting of botanical and geological materials was carried out between November 26 and December 5, after which it was time to proceed to Snow Hill Island. The ice conditions, however, impeded all their efforts.

On December 29, 1902, Andersson, Duse, and Toralf Grunden landed on the west side of the

Antarctic Sound in order to set up a depot at Hope Bay. They were to connect with the party at Snow Hill Island, but if *Antarctic* had not reached Snow Hill Island by February 10, all nine men were to march to Hope Bay to await the ship.

Andersson, Duse, and Grunden failed to reach Snow Hill Island and were forced to return to Hope Bay on January 13. With only summer clothes, they spent the winter in a small stone hut, surviving on penguins, other birds, and some provisions brought from the ship. When not hunting, Andersson searched for fossils from the Tertiary and Jurassic periods, resulting in the discovery of some twenty new species.

Meanwhile, *Antarctic* faced a struggle of 6 weeks in the ice before on February 12, with a severely damaged engine room, it sank 45 km from Paulet Island. The nineteen men, led by Larsen, spent 16 days transporting small boats, clothes, and provisions, as well as a stove, towards safety on Paulet Island. There they built a hut of 5.4×6 m, with stone walls and sails and sealskins for a roof. The health of the party remained fairly good although a young seaman, Ole Wennergaard, died on June 7, 1902. The next spring Larsen took five men and set off for Hope Bay, only to find the small base abandoned.

On September 29, 1903, Andersson, Duse, and Grunden once again left for Snow Hill Island. On October 12 they actually met Nordenskjöld and Jonassen on their way back from their second sledge tour, whilst rounding James Ross Island. After 4 days joint sledging, they reached the southern base. In the coming weeks, Nordenskjöld and Andersson continued with their geological work. The extent of previous glaciations was discussed and judged to be more extensive than at present. On the morning of November 8, later remembered as "the day of the miracle," Bodman and Åkerlundh, the cook, set out on a minor tour and met Captain Julian Irizar, his officers, and crew, sent from Buenos Aires to rescue the members of the expedition. The Snow Hill party was stunned, but their astonishment had increased by midnight. On the very same day, Larsen, Karl A. Andersson, and four crew members from *Antarctic* arrived at Snow Hill Island, having found a message left at Hope Bay indicating that the party there had proceeded to Snow Hill. They had continued to Nordenskjöld's base themselves, helping to avert a catastrophe.

The Snow Hill base was evacuated on November 10, 1903, and soon thereafter the men remaining at Paulet Island were picked up. The rescue was the cause of much festivity in Buenos Aires, and helped set off a debate involving the Swedish Foreign Ministry as to whether Nordenskjöld should accept Argentine transport back to Sweden. Ultimately, the journey home was arranged privately. Shortly thereafter, Selim Birger (brother to the liaison Gunnar Andersson) was sent to the Falkland Islands to retrieve the scientific collections. In late March 1904 he returned to Sweden before the unsuccessful Swedish relief expedition, under the leadership of Olof Gyldén, returned (on April 4, 1904).

The scientific results were published between 1904 and 1920, and Nordenskjöld became a respected scientist in both Sweden and abroad.

Lisbeth Lewander

See also **Antarctic Peninsula; Larsen, Carl Anton; Larsen Ice Shelf; Nordenskjöld, Otto; Royal Geographical Society and Antarctic Exploration; Swedish South Polar Expedition, Relief Expeditions**

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SWEDISH SOUTH POLAR EXPEDITION, RELIEF EXPEDITIONS

On February 12, 1903, *Antarctic*, the expedition ship of Otto Nordenskjöld's Swedish South Polar Expedition, sank some 45 km from Paulet Island. Although it would still be some months before the disaster would be known to the outside world, members of the expedition had earlier established with various people in Sweden and Argentina that if *Antarctic* had not reached the Falkland Islands by April 30, 1903, a relief expedition should be sent out. During April 1903 a number of Swedish scientists, including Alfred Gabriel Nathorst, from the Museum of Natural History in Stockholm, presented a bill to raise both private and governmental funding for this relief. A few members of Parliament expressed the opinion that a privately funded expedition should also be rescued by private means, and, indeed, Nordenskjöld's relatives raised significant sums, but the Swedish Parliament also granted the sum of 200,000 Swedish crowns. In addition, the Swedish navy released Captain Olof Gyldén to command a Swedish relief expedition, with the sole mission of rescuing the Swedish South Polar Expedition. The relief expedition departed Sweden on August 18, 1903, aboard the Norwegian whaler *Frithiof*.

Rescue activities were also launched in several other countries. William Speirs Bruce's Scottish National Antarctic Expedition and Jean Baptiste Charcot's French Antarctic expedition were among the potential rescuers. Charcot, initially heading for the Arctic, switched in haste to the Antarctic and the rescue. However, Charcot's expedition was delayed and did not join the final phases of the rescue operation. Instead, the actual rescue was carried out by the Argentine Captain Julian Irizar aboard the corvette *Uruguay*. Irizar visited Stockholm and London and initially, in spring 1903, liaised to some extent with the Swedish government. The route his expedition was to follow was on the agenda, as was possible assistance from Argentina to Gyldén's expedition. Ultimately Irizar was instructed to await the French and Swedish expeditions until the first week in November. Thereafter, he should set off for Graham Land in *Uruguay*.

The operation included several dramatic events. On November 8, representatives of the Argentine navy met two members of Nordenskjöld's party in the vicinity of Snow Hill Island. In the meantime, a six-man party led by Captain Carl Anton Larsen had struggled to reach Snow Hill Island, setting out from Paulet Island, where nineteen people had wintered out the harsh condition in a stone hut. Larsen and his men arrived just in time because the plan was for *Uruguay* to leave as soon as possible due to fear of severe ice conditions. Yet another group of scientists, who had spent a winter in miserable conditions at Hope Bay, had joined Nordenskjöld's main party in October. Through these spectacular events, three widely dispersed parties had managed to reach each other at the last moment, and as a result Nordenskjöld and his expedition departed safely, picking up the men remaining at Paulet Island on the way north.

Meanwhile, the Swedish relief expedition had tried to get in touch with the Argentine expedition whilst on its way southwards, only to realise that *Frithiof* was lagging far behind. Stops were made at the Cape Verde Islands, Buenos Aires, and Ushuaia. The openly admitted competition between France and Argentina was beneficial to neither the French nor the Swedish. On December 4, 1903, after a march of some 20 km, Gyldén, scientist Axel von Klinckowström, and the expedition's medical doctor reached the Snow Hill Island base, only to find it abandoned and a letter from Nordenskjöld detailing the expedition's departure on November 10, 1903. Gyldén was requested to sail for the Falkland Islands in order to collect scientific material left there by Nordenskjöld, but Gyldén refused this request because his ship was in urgent need of repair, and he wanted to keep the costs down. He therefore returned to Sweden without delay, via Buenos Aires, Le Havre, and Bremerhafven. *Frithjof* was practically shipwrecked en route, and the expedition returned to Sweden without any positive media attention. In the lengthy press debate that followed, Gyldén was taken to task for his failure to locate Nordenskjöld in time and for not recovering the scientific collections.

On December 9, 1903, *Uruguay* safely reached Buenos Aires. Before entering the inner harbours, the ship was repaired and painted, in preparation for its participation in the magnificent festivities that had been planned. Argentine and Swedish expedition accounts, as well as South American and European press reports, presented uniform images of the mass greetings given to *Uruguay* and the members of the Swedish South Polar Expedition.

Lisbeth Lewander

See also **Charcot, Jean-Baptiste; French Antarctic (*Français*) Expedition (1903–1905); Larsen, Carl Anton; Nordenskjöld, Otto; Scottish National Antarctic Expedition (1902–1904); Swedish South Polar Expedition (1901–1904)**

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SYNOPTIC-SCALE WEATHER SYSTEMS, FRONTS AND JETS

Synoptic-scale weather systems are large, cyclonic disturbances or depressions (lows) that are a significant feature of the atmospheric circulation over the Southern Ocean and Antarctic coastal region. Air circulates around the centres of these lows in a clockwise direction, with the winds near the surface spiralling in towards the centres of the vortices. Lows are characterised by strong winds, large-scale ascent, and the formation of cloud and precipitation, which is often concentrated along frontal bands. Any broadscale satellite picture of the Antarctic continent and the Southern Ocean reveals a large number of major lows over the ocean areas around the continent. The individual lows can be identified on satellite pictures by their high, cold frontal cloud bands wrapped around the centres of the depressions.

Depressions typically have a horizontal length scale of 1000–3000 km and a lifetime of 1–3 days, although some lows can last longer. A vast range of synoptic-scale weather systems is found around the Antarctic, and in fact a spectrum of weather systems exists from very small vortices to major depressions occupying extensive areas of the Southern Ocean. The smaller, shorter-lived cyclonic vortices are called polar lows or mesocyclones and are dealt with in a separate section.

Synoptic-scale lows play a crucial role in the general circulation of the Southern Hemisphere through their part in the poleward (equatorward) transport of warm (cold) air towards the Antarctic (tropics). This happens through the individual lows carrying warm, midlatitude air poleward on their eastern flank and cold, polar air equatorwards on their western side. The lows also release large amounts of latent heat at high latitudes when water vapour condenses into cloud. Without this poleward transport of heat the Antarctic would be much colder than presently recorded in winter when there is no incoming energy from the Sun.

The lows are also extremely important in the weather that they bring to the Antarctic coastal zone. Synoptic-scale lows are responsible for many of the strong wind events that occur around the periphery of the Antarctic, and they also give the largest falls of precipitation. The strong winds give rise to major blowing snow events, which are a serious hazard to operations. They can also break up and move sea ice and have a significant impact of air-sea interactions around the continent.

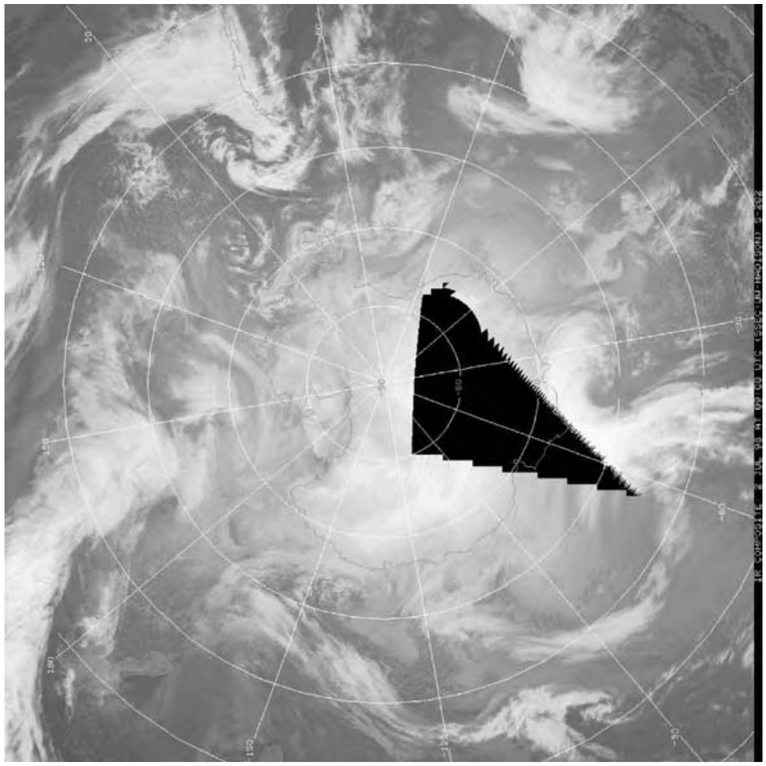
Analyses of satellite pictures and routine surface pressure charts have shown that the largest number of depressions is found just north of the Antarctic coast, at the latitude of the circumpolar trough over 60°–70° S. The lows here generally consist of two types, which satellite studies suggest occur with about equal frequency. Firstly, lows are observed that have developed in midlatitudes and spiralled in towards the Antarctic. The second type of system develops at the latitude of the circumpolar trough and then generally moves towards the east. The net result of so many depressions in the circumpolar trough is to give climatological easterly winds along the coast and westerlies on the northern flank of the circumpolar trough.

The tracks followed by the depressions is determined to a large extent by the winds in the mid- to upper-troposphere, which in turn are dictated by the location and amplitude of the atmospheric long waves (Rossby waves). When the long waves have a relatively small amplitude, the lows tend to follow a more zonal (west to east) track. In contrast, the depressions move in a more meridional direction towards the Antarctic coastline when the Rossby waves have a greater amplitude.

Very few synoptic-scale depressions penetrate onto the high Antarctic plateau, with most of the lows moving eastwards parallel to the coast once they reach the circumpolar trough. However, if the Rossby waves have a very large amplitude the steering level winds may be almost from the north so that the lows arrive at the continent almost perpendicular to the coast. In such a situation the steering level winds may extend for a considerable distance into the interior of the continent, and this scenario is the one most commonly associated with active synoptic-scale lows that are observed on the Antarctic plateau. When large-scale lows reach the interior of the Antarctic they bring very anomalous conditions, including relatively high temperatures, moderate snowfall, and strong winds.

The development of new lows is called cyclogenesis, and this can come about via a number of mechanisms. These are the same as occur in midlatitudes so they will only be described briefly here. Most lows develop via baroclinic instability, which is the formation of lows on horizontal temperature gradients where there is a conversion of the potential energy associated with the temperature gradient into the kinetic energy of the low. Horizontal temperature gradients are rather weak over the interior of the Antarctic so very few large lows develop there.

The greatest number of cyclogenesis developments takes place within the circumpolar trough, with a rapid decrease into the interior of the Antarctic and a slower decrease towards midlatitudes. The circumpolar trough, just north of the Antarctic coast, is a



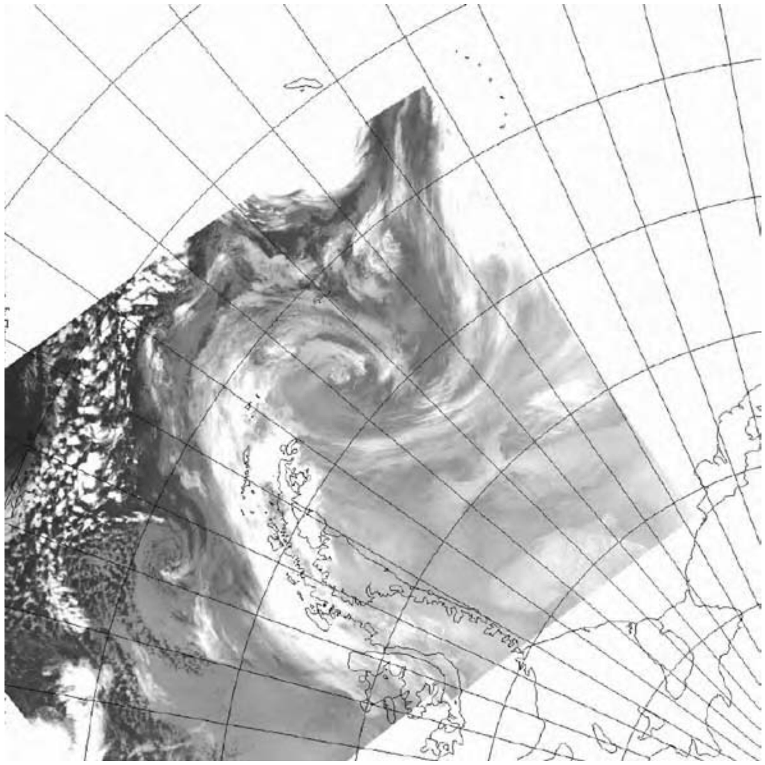
A composite infrared satellite image of the Antarctic and Southern Ocean showing the cloud associated with synoptic-scale weather systems and fronts. Cold clouds appear white while the relatively warm ocean is dark. The triangular black area indicates where no imagery was available. (Image provided by the Space Science and Engineering Center, University of Wisconsin-Madison.)

zone where relatively mild, midlatitude air masses moving southwards meet cold, continental air coming off the Antarctic continent. We therefore observe many lows developing in this zone. As lows move eastwards around the Antarctic the serial development of new depressions from mature or declining lows is often observed within the circumpolar trough. This often occurs because well-developed lows bring relatively warm air southwards on their eastern side which meets cold, polar air that has come off the continent. This can lead to a strengthening of the horizontal thermal gradient and the development of new lows. Sequences of satellite pictures therefore frequently show serial development of depressions, with new lows forming in the vicinity of existing depressions, often in association with frontal cloud bands.

The distribution of cyclone developments around the continent is rather uniform, which is perhaps not surprising given the fairly symmetric nature of the Antarctic orography. However, there are maxima over the Amundsen Sea, in the Indian Ocean sector, and close to the Greenwich Meridian.

One type of development that is frequently observed to the east of the Antarctic Peninsula is lee cyclogenesis. This occurs as air flows perpendicular across mountain barriers and results in an increase in cyclonic vorticity (spin) in the lee of the mountain range. Lows can form in isolation to the east of the Antarctic Peninsula or develop as a front crosses the mountains in association with a low over the Bellingshausen Sea. Lows that develop in the lee of the Peninsula tend to move towards the east, crossing the Weddell Sea and sometimes moving towards the northeast and joining the main belt of storms to the north of the Weddell Sea. Besides the Antarctic Peninsula, there are no other major orographic barriers where the prevailing wind flows perpendicular to the mountains, so the western Weddell Sea is unique in the Antarctic as a major area of synoptic-scale lee cyclogenesis. Lee cyclogenesis events observed in other parts of the Antarctic tend to be much more sporadic or occurring on smaller horizontal scales.

The decline and dissipation of depressions is called cyclolysis and is the result of the cessation or weakening of the forcing factors that maintain the structure of the depressions. The distribution of cyclolysis events around the Antarctic during winter is remarkably similar to the distribution of cyclogenesis, with a maximum at the latitude of the circumpolar trough.



An infrared satellite image of a synoptic-scale low pressure system centred just northeast of the tip of the Antarctic Peninsula.

The coastal region of the Antarctic is therefore characterised by the formation of many depressions, the systems moving towards the east and then dissipating at approximately the same latitude. Although cyclolysis is a feature of all sectors of the Antarctic, some areas experience more events than others. One such area is the Bellingshausen Sea, to the west of the Antarctic Peninsula. Depressions frequently decline here as they become slow-moving when they come up against the high orographic barrier of the Peninsula. There is also frequent cyclolysis just north of the coast of East Antarctica.

There have been few detailed case studies of the structure of synoptic-scale lows around the Antarctic because of the lack of three-dimensional *in situ* data within the lows. Therefore, most of our knowledge of the form of these systems has come from analyses of sequences of satellite images. Of course these show only the cloud associated with the lows, but much can still be gleaned regarding the life cycle and form of the lows from these images. A few lows over the Southern Ocean have the classical structure of midlatitude cyclones with well-defined warm, cold, and occluded fronts. This is the case with one low that was centred to the northeast of the tip of the Antarctic Peninsula with a warm front extending down the spine of the Peninsula and a cold front lying east-west along the northern Weddell Sea. However, studies show that such systems are very much the exception and that most lows have a much less clear structure.

The Antarctic coastal region is characterised by extensive cloud and many lows have only a weak cloud signature within an extensive field of fairly uniform, relatively featureless cloud. The task of identifying the locations of fronts within synoptic-scale lows, which is important for weather forecasting, is therefore not easy. Satellite pictures have also revealed that many large lows have multiple centres. This is particularly the case for declining depressions, when the low may develop a number of small, mesoscale lows within the large area of low pressure. If a short-wave, upper level trough moves over one of these mesoscale lows it can cause it to develop into a new, large-scale low. So sequences of satellite images of the Southern Ocean reveal a highly dynamic picture of depression formation and dissipation that is in stark contrast to the view held in the presatellite era of the Antarctic coastal region being characterised by only the decline of depressions.

Atmospheric fronts are found at the boundaries between air masses of different characteristics and are usually apparent on satellite pictures as bands of cloud indicating the ascent of air that takes place in these areas. Most fronts are found at the boundaries of air masses with different temperatures, and the greater the temperature difference the more active the front tends to be. In the case of active fronts, there is strong vertical motion that results in deep cloud that is very apparent on infrared satellite pictures via the very cold cloud tops.

The most active fronts tend to be associated with deep, synoptic-scale depressions that form on strong horizontal temperature gradients. Such very active lows usually form in midlatitudes, and the most marked, high frontal cloud bands are often found in midlatitudes and the northern part of the circumpolar trough.

Weak fronts can frequently be observed on satellite images as linear cloud features, often well removed from the large weather systems. Such fronts often indicate the boundaries between air masses of slightly different characteristics. For example, a minor front can often be seen running parallel to the edge of the sea ice separating warmer, moister air over the ice-free ocean from colder, dryer air lying over the sea ice.

Jets (or jet streams) are narrow belts of strong winds that are found in association with moderate or strong horizontal temperature gradients. Two types of jets are found. Firstly, those in the upper troposphere associated with the atmospheric long waves and the major storm tracks and depressions. These can be thousands of kilometres in length, and the location of these varies considerably on a day-to-day basis. They are always closely associated with the large synoptic-scale lows. The strongest jets are found in midlatitudes in association with strong horizontal temperature gradients existing through deep layers of the atmosphere where the most active depressions are located. The second type of jet is found at much lower levels and is usually only tens or hundreds of kilometres in length. They are found above the warm, cold, and occluded frontal surface associated with synoptic-scale lows, along with some other minor frontal zones.

The accurate forecasting of the location and strength of synoptic-scale lows, along with the associated winds, cloud, and precipitation is of critical importance to the complex logistics that takes place on and around the Antarctic today. Many nations operate weather forecasting centres at their stations that provide routine forecasts for their aviation, maritime, and deep-field operations. The forecasting of the movement and development of major depressions for periods beyond about 6 hours ahead is today based almost entirely on the output of computer models runs outside the Antarctic. Fields of surface pressure, winds, and heights at upper levels and precipitation from global models are sent several times a day to the stations and used to infer the future locations of the major weather systems. The current generation of models provide very good guidance on the locations and depths of the major lows for several days ahead, and they have some skill up to about a week ahead. A number of nations are now running higher resolution, limited area models either on the stations or at forecast centres outside the Antarctic. These are better able to represent the complex orography of the Antarctic in areas such as the Antarctic Peninsula.

For forecasting up to about 6–12 hours ahead extensive use is made of sequences of satellite images. These provide a dynamic illustration of the recent movement of the weather systems and their frontal bands, along which most of the precipitation is located. Such imagery allows the locations of the weather systems to be extrapolated over the coming hours, providing an essential supplement to the model output.

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See also **Meteorological Observing; Polar Lows and Mesoscale Weather Systems; Polar Mesosphere; Weather Forecasting; Wind**

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TARDIGRADES

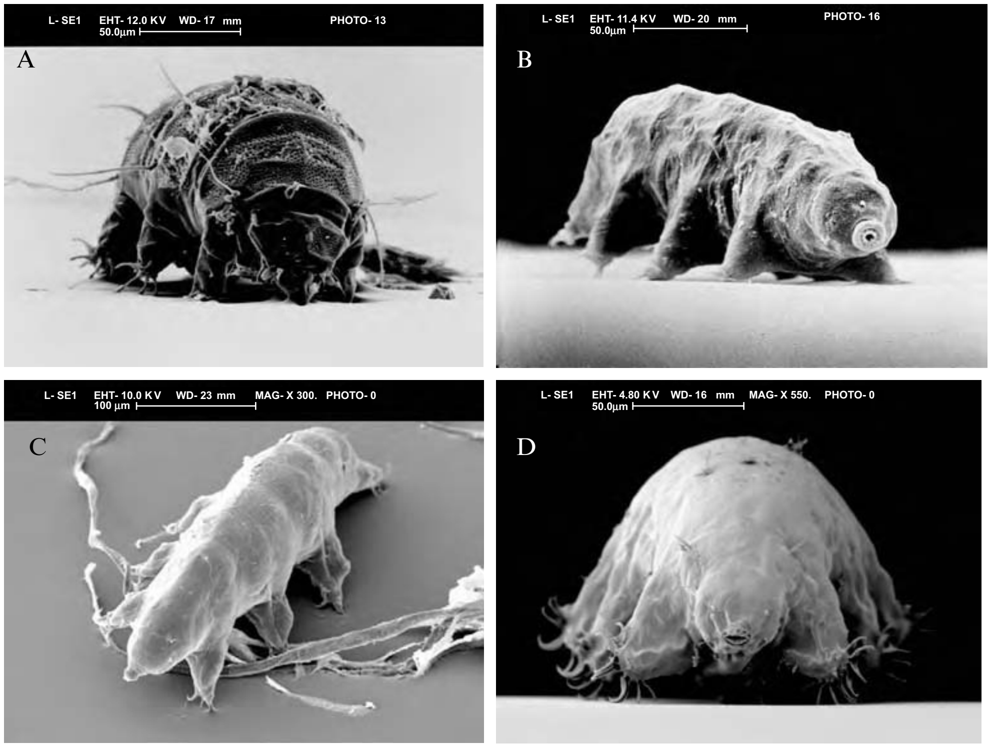
One of the "lesser-known" phyla, the Tardigrada are a cosmopolitan group, including approximately nine hundred species worldwide, found in diverse habitats within freshwater, terrestrial, and marine environments. In the early 1770s, a German pastor, Johann August Ephraim Goeze, described the animals as *kleiner Wasserbär,* giving them their descriptive common name of "water bears." About the same time, an Italian monk (Lazzaro Spallanzani), describing their lumbering gait, called them *il Tardigrado* (*tardi,* slow, and *grado,* walker), from which are derived both the Latin (Tardigrada) and the common (tardigrade) names. The phylum is divided into two classes: the Heterotardigrada, which includes mainly the marine and "armoured" terrestrial tardigrades; and the Eutardigrada, which comprises the "unarmoured" freshwater and terrestrial species.

Tardigrades are roughly cylindrical with four pairs of short stubby legs, terminating in claws. Their body length varies from about 50 μm (0.05 mm), after hatching from the egg, to a maximum of 1200 μm (1.2 mm) in a few exceptionally large species. Adults of most species fall within the range of 200–500 μm. Tardigrades have a complete digestive system and a fluid-filled body cavity (haemocoel) that functions in circulation and respiration. The nervous system consists of a dorsal lobed brain and ventral nerve cord with fused paired ganglia.

Tardigrades are found wherever "free" water is available, even intermittently. In terrestrial and freshwater habitats this includes mosses, lichens, leaf litter and soils, sediments, algal mats, and submerged plants, or within the interstices of sandy substrata. In marine environments tardigrades are present from the intertidal coastal zone of sandy shores, algal holdfasts, and shells of barnacles on rocky shores through the deeper shelf zone to the abyssal depths. They are one of the very few animal phyla that are found from the world's highest mountains to the deepest seas.

The relationship of the Tardigrada within the hierarchy of animal classification has been debated for many years, with no satisfactory conclusion as to whether they should be aligned with the Aschelminthes (nematodes, rotifers, etc.) or Arthropoda (crustaceans, insects, etc.). More recently, molecular studies (in particular those using 18S rRNA) have established a new grouping of "Ecdysozoa," made up of invertebrates that moult. This has offered an explanation of the morphological similarities between tardigrades, the arthropod line, and the aschelminth complex, and indicates that tardigrades are a sister group of the arthropods.

Early microscopists were fascinated by the ability of tardigrades to be "resurrected after death." This ability, shared with other groups such as Rotifera and Nematoda, is a form of cryptobiosis, or suspended animation, where the animal can cease (detectable) metabolism during unfavourable conditions (e.g., drought, extreme cold) and reactivate when conditions are again suitable for life. Life history attributes such as parthenogenetic reproduction (in the absence of males), well-developed cold tolerance, and resistant anhydrobiotic life stages are thought to preadapt tardigrades for the colonisation of new or remote habitats, harsh conditions, or for survival in refugia



(A) *Echiniscus punctus,* terrestrial Heterotardigrada. (B) *Macrobiotus furciger,* terrestrial Eutardigrada. (C) *Ramazzottius* sp, terrestrial Eutardigrada. (D) *Echiniscoides sigismundi,* marine (intertidal) Heterotardigrada.

(e.g., in the Antarctic, small pockets of terrestrial habitat that were not obliterated during glacial advances).

Tardigrades from the terrestrial habitats in the Antarctic and sub-Antarctic islands number approximately seventy species, with more being added as new sites are studied and taxonomic knowledge advances. Marine species are present in the Southern Ocean, and have been reported from the European "Polarstern" Study (EPOS) cruise (1989) to the Weddell Sea and the Antarctic deep-sea biodiversity (ANDEEP) programmes (2001) to the Scotia Arc and the Weddell Sea. To date, only four marine species have been described in literature from the Antarctic, but as very few areas have been specifically studied for marine tardigrades, the potential for new records and new species is very high.

Though microscopic in size, tardigrades are important to the biomass of Antarctic terrestrial sites, where competition and predation are more reduced than in equivalent temperate or tropical sites. Indeed, the most southerly inland sites studied in detail, on nunataks (rocky mountain tops exposed from surrounding glaciers) in Ellsworth Land (c. 75°–77° S, 70°–73° W), revealed an exceptionally simple faunal community including only five tardigrade and two rotifer species. All other fauna normally present in Antarctic terrestrial communities (particularly nematode worms and microarthropods) were absent. Population densities of tardigrades in the terrestrial Antarctic are generally between 10 and 1000 times greater than those of temperate or tropical zones.

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See also **Algal Mats; Anhydrobiosis; Lichens; Microbiology; Mosses; Nematodes; Rotifers; Soils**

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TELECONNECTIONS

A teleconnection is a positive or negative correlation in the fluctuations of an atmospheric field, or fields, at widely separated points, and is mostly applied to variability that occurs on monthly or longer timescales. Several teleconnections can be found linking Antarctica with the rest of the world and within the South Polar region.

The dominant mode of atmospheric variability around Antarctica is the Antarctic Oscillation (AAO), or as it now more often called, the Southern Annular Mode (SAM). This zonally symmetric mode is essentially a teleconnection between approximately 40° S and 65° S. A meridional index can be constructed by taking the pressure difference between high and low latitudes, and this index can explain over 50% of the mean monthly variance surface pressure over Antarctica.

Another mode of variability that can be found around Antarctica is characterised by an atmospheric wave number 1 (one crest and one trough on a latitude circle around the Earth) in the pressure/height fields. This pattern produces opposing anomalies between the Australia–New Zealand and Antarctic Peninsula–South America sectors. This mode can be represented by a Trans Polar Index (TPI), constructed by taking the mean sea-level pressure anomaly difference between Hobart and either Stanley, Falkland Islands or Grytviken, South Georgia.

These modes of variability (and others) are described in detail elsewhere in this encyclopaedia. They explain most of the teleconnections found within the middle and high southern latitudes. However, teleconnections do exist between Antarctica and the tropics and even possibly the Northern Hemisphere. One of the best-known teleconnections between the tropics and Antarctica is that associated with the El Niño/Southern Oscillation (ENSO). A correlation can be found between the sea-surface temperature in the tropical Pacific and the pressure in the Amundsen–Bellinghausen Sea (ABS) or the temperature on the west coast of the Antarctic Peninsula. These correlations are rather weak. The correlation with pressure in the central ABS is 0.5, which is significant, while the correlation with temperature on the west of the Peninsula is –0.23, which is not significant at the 90% level. This teleconnection is associated with planetary scale waves in the atmospheric circulation. These waves are generated in the tropics by the divergent flow aloft resulting from deep tropical convection and propagate polewards to high latitudes. The tropical forcing mechanisms for the Rossby wave and the factors affecting the propagation of the wave through mid latitudes are complex and it is not surprising that simple linear correlations are often weak.

Despite the fact that the teleconnection between the tropical Pacific and the circulation around Antarctica is often weak, an ENSO signal is found in ice cores taken at the South Pole and in some high-latitude living organisms. In an ice core taken from South Pole it was found that levels of methanesulfate, which is normally associated with marine biogenic activity, could be correlated with ENSO and with southeastern Pacific sea-ice variations. Some correlations have been found between ENSO and pelagic ecosystems. The age structure of crabeater seals around the Antarctic Peninsula, juvenile leopard seal occurrence at Macquarie Island, and Weddell seal reproductive rates have all shown peaks at around the 4- to 5-year interval that is normally associated with ENSO and generally in phase with the ENSO signal. However, these signals do not show a completely consistent picture, probably because we do not understand the complex, nonlinear connections between the tropical pacific and the sea ice and ocean circulation around Antarctica.

The ENSO–Antarctic teleconnection is associated with one of the Pacific–South American (PSA) modes. The PSA modes are the two most dominant modes of variability of the Southern Hemisphere circulation. The two patterns are in quadrature with each other and are dominated by a wave number three wave train propagating from just north of Australia across the Pacific and South America and into the South Atlantic. The amplitude of the wave pattern is large in the PSA sector. ENSO produces variations in the PSA pattern on interannual time scales; however, variations in the PSA can be found on much shorter time scales. Variations in the PSA modes with timescales from weeks to months are found and these variations are thought to be associated with convection anomalies in the western Pacific and Indian oceans.

A study using a numerical model has shown that changing the radiative properties of Antarctica clouds can create significant changes in the tropics and even the extratropics of the Northern Hemisphere. This suggests the possibility of some Tropical–Antarctic teleconnections being forced from the Antarctic. Studies looking at the connection between sea-ice extent around Antarctica and the rest of the world reveal strong teleconnection between the sea ice in close to the Antarctic Peninsula and ENSO, which are assumed to be driven by the tropics, but also connections with Indian Ocean sea-surface temperature and tropical Pacific precipitation. With these last two connectivities it is not possible to identify the direction of causality; we may have the Antarctic climate driving variability in the tropics.

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See also **Antarctic Peninsula; Bellingshausen Sea, Oceanography of; South Georgia**

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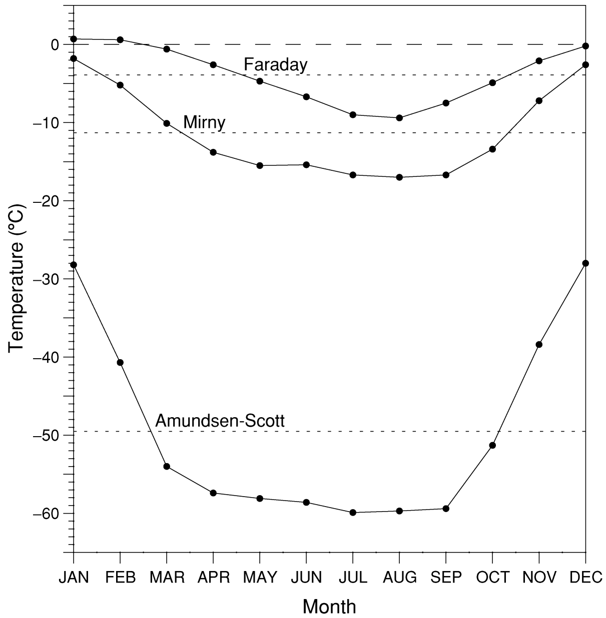
TEMPERATURE

Several factors combine to cause Antarctica to be the coldest continent. Antarctica is located at high latitudes, which means that it receives less solar radiation per year than lower latitudes and thus acts as a heat sink for the Southern Hemisphere. The high albedo of the snow and ice, which covers more than 99% of the continent, reflects 80%–90% of incident solar radiation, hence enhancing the cold temperatures. The extreme dryness of the air causes any heat that is radiated back into the atmosphere to be lost to space instead of being absorbed by water vapour within the atmosphere. Furthermore, Antarctica is also the highest continent, with a median elevation of 2150 m asl. At its highest the interior, known as the Antarctic Plateau, exceeds 4000 m asl. Its domed shape, with relatively steep gradients near the coast, prevents the frequent intrusion of warmer maritime air from coastal cyclones. The coldest temperatures on Earth are found during the polar night on top of the plateau, where no direct sunlight is received during winter months and where slopes are sufficiently shallow to prevent mixing through significant katabatic wind flow. The lowest measured temperature, –89.2°C, was recorded at Vostok station (78.5° S, 106.9° E, 3488 m asl) on 21 July 1983, but it is estimated that temperatures on parts of the Plateau may occasionally dip below –100°C.

Radiosonde (balloon) soundings reveal a strong temperature inversion above the Antarctic surface that is maintained by radiative cooling of the surface and lower atmosphere as described previously. Thus, as we might intuitively expect, the inversion is strongest on the plateau during the polar night (winter), when there is no incoming solar radiation and surface cooling is at a maximum. However, significant inversions can occur at any time of year, even in coastal regions. The resulting radiation deficit at the surface is balanced by turbulent heat flux from the atmosphere, whereas at the top of the boundary layer this flux divergence is zero (by definition). Hence, the boundary layer cools relative to the surface, producing a stably stratified temperature profile and surface inversion. When strong katabatic winds occur they mix the cold air vertically through a deep layer, destroying the inversion; therefore, near-surface temperatures covary strongly with wind speed.

Antarctica may be separated into three distinct zones based on the annual temperature cycle. In the northern part of the Antarctic Peninsula (Faraday), monthly mean temperatures exceed zero in summer, and here the annual cycle of temperature has a form found across many regions of the Earth, with a broad maximum in summer and a slightly shorter winter minimum. However, on the Antarctic Plateau (Amundsen-Scott) the form of the cycle changes completely. As well as temperatures being much colder, summer is now very short (December/January) with rapid changes in temperature defining the ends of a long or coreless winter period that encompasses several months with broadly similar mean temperatures. This rapid cooling and warming is due to the abrupt removal and return of surface radiation south of the Antarctic Circle at the beginning and end of the polar night. The annual temperature cycle at Mirnyy, representative of East Antarctic coastal stations, has a profile in between the other two regions mentioned: while monthly temperatures are much closer to those on the peninsula, the winter period is much longer, more similar to the polar plateau. Above the inversion, temperatures in the Antarctic troposphere follow a broadly similar seasonal pattern to that observed at the surface at East Antarctic coastal sites. The range between maximum and minimum monthly mean temperatures is ~10°C at 500 hPa (~5 km asl) across the whole continent.

The significant modification of the seasonal cooling that produces the coreless winter is thus observed



Annual cycle of temperature at Faraday (Antarctic Peninsula), Mirny (coastal East Antarctica), and Amundsen-Scott (Antarctic Plateau). The dotted line shows the mean annual temperature.

across much of Antarctica. It is a consequence of the semiannual oscillation (SAO), a twice-yearly expansion and contraction of the circumpolar low-pressure belt around Antarctica. This results from the different thermal capacities of the continent and surrounding Southern Ocean. The magnitude of temperature modification by the SAO appears largely determined by the strength of the winter surface-temperature inversion. Hence the impact is largest on the plateau, followed by coastal East Antarctica and then Peninsula stations: this can be observed in the above figure with regard to the duration of the coreless winter at the three stations. Heat stored within the winter snowpack also dampens any temperature fluctuations. In coastal East Antarctica, the coupling between the SAO and near-surface temperature can be explained by seasonal changes in the meridional circulation brought about by the former. Its influence on winter temperatures on the plateau is less well understood, although stronger katabatic wind drainage during this season may be important.

Antarctic temperatures are also influenced by climate variability in other parts of the earth, as evidenced by so-called teleconnections. The principal mode of variability in the Southern Hemisphere is the Southern Annular Mode (SAM), which comprises zonally symmetric synchronous pressure anomalies of opposite sign in Antarctica and the mid-latitudes. Statistical studies suggest that SAM variability impacts temperatures across much of Antarctica, although not necessarily in the same direction. Also important is the Pacific South American (PSA) pattern; this reflects the phase of tropical El Niño–Southern Oscillation (ENSO) variability and primarily affects Antarctic Peninsula winter temperatures.

The longest Antarctic temperature records are from manned stations, and the longest of all, at Orcadas in the South Orkney Islands, now exceeds 100 years. However, with a few exceptions in the Antarctic Peninsula, most temperature records did not begin until the International Geophysical Year of 1957–1958. Until relatively recently temperatures were observed manually, but now many countries have automated their data collection, using similar technology to that employed in Automatic Weather Stations (AWSs). These allow temperatures to be obtained from the more inaccessible parts of Antarctica, typically coastal islands, ice shelves, or the interior. Analysis of Global Telecommunications System (GTS) data reveals that there are now more Antarctic observations derived from AWSs than from manned stations.

Current mean annual air temperature at the snow surface is often estimated by assuming that it is equal to the snow temperature measured at a depth of 10 m. The accuracy of this assumption is dependent on the snow stratigraphy, shape of the annual cycle of temperature, and long-term trends, but methodologies are available to remove these effects. As a 10-m core can be drilled relatively quickly and simply, this is a very useful way to obtain temperature measurements away from manned stations. Longer-term temperatures can be obtained from chemical proxies within ice cores, such as the oxygen–isotope ratio. The deepest ice core ever drilled was recently completed by the European Project for Ice Coring in Antarctica (EPICA) at Dome C (75.1° S, 13.3° E); it is over 3270 m in depth and encompasses more than 900,000 years.

Today surface temperatures across the whole of Antarctica can be obtained from satellite instruments. Two types of data have been utilised to produce long time-series of temperatures appropriate for climate studies. First, the thermal infrared channels of the Advanced Very High Resolution Radiometer (AVHRR) instrument have provided a good estimate of near-surface air temperature at a resolution of ~5 km since 1979. The principal problem with this type of data is that it can only be obtained in cloud-free conditions. As clouds have a positive effect on surface temperatures over high-reflectance surfaces, this leads to a negative clear-sky bias in average AVHRR-derived temperatures, particularly in very cloudy regions such as the Antarctic Peninsula. Passive microwave brightness temperatures, also available since 1979, from the Scanning Multichannel Microwave Radiometer (SMMR) and subsequently the Special Sensor Microwave Imager (SSM/I) instruments are unaffected by cloud cover. However, their spatial resolution is only 25 km and their exact relationship with surface temperature is dependent on temperature and emissivity changes in the snowpack through which the radiation penetrates. Nevertheless, both these datasets are very useful in examining spatial temperature variability across Antarctica at regional and continental scales.

Continent-wide temperatures may also be derived from numerical weather prediction models, typically with a spatial resolution of about 100 km. Such analyses are useful for examining spatial variability in temperature, similar to satellite data. However, in comparison with observations there can be significant biases, even in relatively homogeneous regions like the Antarctic Plateau. Errors may be caused by incorrect elevations used in the model or by deficiencies in surface and boundary flux parameterisations, which are often tuned for midlatitudes.

The largest changes in temperature from station observations are seen in the Antarctic Peninsula. At Faraday, on the western coast, the annual warming of almost 3°C between 1951 and 2004 is believed to be the largest recorded anywhere on Earth over the last 50 years. A statistically significant warming has occurred throughout the northern part of the Peninsula. However, a seasonal analysis indicates that those stations on the north and west coasts have the greatest temperature rise in winter while those on the east coast show the most marked changes in summer and autumn. This is because different aspects of climate change are primarily responsible for the warming in the two regions. For example, in winter there is a strong negative correlation between western coastal temperatures and the extent of sea ice west of the peninsula in the Bellingshausen Sea. From sporadic ship reports in the 1950s and 1960s and satellite observations from the 1970s it appears that, uniquely for Antarctica, there has been a reduction in winter sea ice in this area. This has allowed greater seasonal exchange of heat from the ocean to atmosphere, thus contributing to the winter warming. In the northeast peninsula, the strength of the westerlies in autumn and summer has increased in recent decades, leading to a higher frequency of air masses passing eastward across the Antarctic Peninsula in these seasons. This relatively warm maritime air has caused a seasonal temperature increase that exceeds 2°C in 40 years, and is responsible for the substantial surface melting that has initiated the collapse of the northern sections of the Larsen Ice Shelf.

Over the full length of records there has been very little statistically significant temperature change across Antarctica away from the peninsula. This is partially a function of the relatively short time-series available and the high interannual temperature variability in coastal regions. The trend with the greatest magnitude is the autumn cooling at Halley. However, the largest and/or most significant seasonal trend is a warming in winter at a number of stations in East Antarctica. There are few distinct regional patterns, although stations in relatively close proximity can reveal similar seasonal trends in temperature (e.g., Mirny and Casey). Amundsen-Scott station, at the South Pole, is the only station to have a cooling in every season: a contemporaneous reduction in wind speeds suggests more stable boundary conditions and hence increased heat loss to the atmosphere as a possible mechanism. Recently, there have been several studies linking a summer/autumn cooling in East Antarctica over the last 30 years or so, with changes in the SAM. Interestingly, this is the same climate change that has caused the strong warming in the northeast peninsula. However, unlike in the latter case, the exact processes through which the mechanism operates are not yet clear.

Relatively little analysis has been undertaken on tropospheric temperature trends above Antarctica although the discovery of the "ozone hole" has led to the stratospheric cooling's being studied in great detail. In contrast, within the Antarctic troposphere there does appear to have been a warming at 500 hPa throughout most of the year during the last 30 years. Despite the shortness of the examined time-series, these trends are often statistically significant and are not limited to the Antarctic Peninsula region. Winter is the season that demonstrates the clearest warming signal with a statistically significant trend above most Antarctic radiosonde stations. At the South Pole, in direct contrast to surface temperatures, those in the troposphere show a warming in all seasons over the period of study.

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See also **Amundsen-Scott Station; Antarctic: Definitions and Boundaries; Climate; Climate Change; Ice–Atmosphere Interaction and Near-Surface Processes; International Geophysical Year; Larsen Ice Shelf; Meteorological Observing; Remote Sensing; South Orkney Islands; Teleconnections**

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TERNS: OVERVIEW

Terns are seabirds in the family Sternidae, previously considered a subfamily, Sterninae, of the gull family Laridae. They evolved from gull-like ancestors and are closely related to the gulls and skimmers. Most terns (two-thirds of all species) belong to the large genus *Sterna*. The other genera are small, though some authorities split the genus *Sterna* into several smaller genera. Although terns are closely related to gulls (Laridae), they are more specialized in terms of nesting habitats, diet, and foraging methods, and their morphology reflects these specializations.

Terns are generally small to medium-sized birds, typically with grey or white plumage, often with black markings on the head. They have longish bills and webbed feet. They are lighter-bodied and more streamlined than gulls, and look elegant in flight with long tails and long, narrow wings. Terns in the genus *Sterna* have deeply forked tails, those in *Chlidonias* and *Larosterna* have less forked tails, and the noddies (three genera) have unusual notched wedge-shaped tails, the longest tail feathers being the middle-outer, not the central or the outermost ones.

Five tern species have been regularly observed in the Southern Ocean: the Antarctic tern *(Sterna vittata),* Kerguelen tern *(S. virgata),* Arctic tern *(S. paradisaea),* South American tern *(S. hirundinacea),* and common tern *(S. hirundo)*. Some of these species are difficult to distinguish from one another.

Antarctic terns are medium-sized and appear very similar to Arctic and common terns, but these last two species occur in the southern summer in nonbreeding or immature plumages. At this time, the plumage of breeding adult Antarctic terns features a black cap and long tail streamers. Both genders have blood-red bills and red legs, while only the juveniles have winter-plumage-like feathers. The differences between Antarctic, Kerguelen, and South American terns are relatively minor—the deeply forked tail with long streamers, relatively short legs, and a strong bill are typical features of Antarctic terns. The juveniles are dark-brown-barred on the upper parts; the cap is black-streaked with buff and is extended below eye level. They are 32–40 cm long, with a body mass of between 114 g and 205 g.

The Arctic tern, a northern breeding species, can be observed in the Southern Hemisphere in the southern summer. The nonbreeders, which regularly occur in Antarctic waters, have white lores, forehead, and fore-crown, and whiter underparts. The upper wings have some dusky areas. The feathers from rump to tail are mainly greyish-white. The bird has a thin, sharp, red bill, sometimes with a black tip, and short, red legs. Its long tail extends beyond the wingtips on the standing bird. They are 33–36 cm long, with a body mass of between 86 g and 127 g. It is most readily confused within its range with the common tern. In winter, the forehead and underparts are white. Juvenile Arctic terns lack the extensive ginger coloration of young common terns.

The common tern as a species of the Northern Hemisphere has a deeply forked tail and relatively long legs. Nonbreeders have white lores, forehead, and fore-crown, and whiter underparts. The upper wings have large dusky areas on the outer primaries, forming a dark wedge. Rump and tail are mainly greyish-white, with darker outer webs to streamers. The bill is always black-tipped and the legs are red or duller in nonbreeding plumage. They are 32–37 cm long, with a body mass of between 92 g and 140 g.

The South American tern is a medium-sized, very-light-coloured species with pale-grey upperparts and paler underparts. This species is distinguished from the other four by its overall grey tone and plumage pattern, especially of the primaries. The red bill is stronger and more curved. The tail is deeply forked with long streamers, and the cap is black, extending to the upper hindneck. They are 41–43 cm long, with a body mass of 172–196 g.

Kerguelen terns have grey plumage, a black cap, and a not-too-deeply forked tail with relatively short streamers. The red bill is relatively short. The underwings are diagnostically grey. The legs are bright orange to dull red. They are 33 cm long, with a body mass of 85–170 g.

Terns have a worldwide distribution. They breed on all continents, including the northern tip of the Antarctic Peninsula. Many terns breed in temperate zones and are long-distance migrants. While about half of the species of terns in the world are primarily birds of tropical oceans and coastlines, small *Sterna* terns occur in a wide range of habitats. They are found in many different breeding habitats: oceanic islands, rocky cliffs, sandy or rocky beaches, coastal marshes, estuaries, inland rivers, and lakes. Only a few species breed inland; the majority nest in coastal areas. During migration, most of the inland species have been observed near the coast and coastal species mostly not far from the coast or seldom away from the continental shelf. Oceanic migration is typical of a few species. A special overwintering area is that of the Arctic tern in the Antarctic pack-ice zone. This species is renowned for its exceptionally long migration route from the high Arctic latitudes to Antarctic wintering areas. There are other migratory species that nest around the Bering Sea (Aleutian tern, *S. aleutica*) and on the Antarctic Peninsula (Antarctic tern, *S. vittata*). Many of these are oceanic species, but others (e.g., little tern in the Old World, least tern in the New World) follow rivers and wetlands to nest well inland.

Accomplished flyers and long-distance travelers, terns are a familiar sight in most coastal waters around the globe. Away from land, terns seen at sea are most likely to be Arctic terns, which are migrants from the Northern Hemisphere. Antarctic, and the less common Kerguelen, terns breed mainly on southern islands in the sub-Antarctic, the former also being found on the Antarctic Peninsula. Antarctic terns migrate several thousand miles each winter to feed in coastal South African waters.

The common tern is a widespread breeder in the temperate zone of the Northern Hemisphere (to tropical West Africa) and then migrates in high numbers to the Southern Hemisphere in winter. The wintering areas extend south to South Africa, Australia, and southern South America, but not south of the Polar Front. The world population is estimated to be between 250,000 and 500,000 breeding pairs. Arctic terns breed in the northern Holarctic and winter south of South America and South Africa, and in large numbers in sub-Antarctic and Antarctic waters. The world population is estimated to be 500,000 breeding pairs.

The South American tern breeds on the coastlines of South America between Peru and Brazil to Tierra del Fuego, including the Falkland Islands, but not south of the Polar Front. In the winter the birds migrate to the north. Antarctic terns breed from Tristan da Cunha to sub-Antarctic islands and south to the Antarctic Peninsula. The population consists of about 50,000 breeding pairs. Kerguelen terns breed on sub-Antarctic islands of the Indian Ocean. The population totals approximately 25,000 breeding pairs.

Most species of this group, which is present around the world, have a more restricted range. The global population sizes of tern species range from a few thousand to tens of millions. The smallest population is that of the Kerguelen tern, a breeding species of the Southern Ocean. Some species are threatened. Egging, hunting, exploitation for feathers, and destruction of nesting habitats are the most common reasons for population decreases. Locally, a high density of predators and human disturbance are the main reasons for low breeding success.

Many terns of the Northern Hemisphere are long-distance migrants, and the Arctic tern probably sees more daylight than any other creature, since it migrates from its northern breeding grounds to Antarctic waters. Other species migrate to the tropics or to the Southern Hemisphere. They migrate partly in huge flocks that sometimes include different species. The time spent by terns in the colonies or on their migration routes varies greatly among species.

Terns are fairly specialized foragers, but not complete specialists. Different species have different feeding methods. Plunge-diving includes flights back and forth at a height of 3–15 m above the water to search for prey below the surface. After fixing the location of prey, they plunge directly into the water. Normally they submerge themselves completely. Sometimes they pursue their prey underwater for a short distance. Normally they leave the water just after submerging and catching their prey. Another method is hover-dipping. This involves hovering 1–2 m above the water and dropping down to seize food items from the surface. Contact-dipping involves flying closer to the water, swooping down, and plunging only the bill under the surface, especially when there is plenty of prey near the surface. In this case contact-dipping will be repeated frequently. A special method is aerial-dipping: in this case, there is no contact with the water surface. Surface-dipping, a rare feeding technique for terns, features swimming or sitting on the surface of the water.

Most terns prefer aquatic (freshwater or marine) feeding areas and few species forage in terrestrial habitats. Most terns and noddies prey on fish by diving, often hovering first, but the marsh terns *(Chlidonias)* pick insects off the surface of fresh water. Terns glide only infrequently, but a few species, notably the sooty tern, will soar high above the sea. Terns are quite gregarious by nature, fishing in flocks of up to several hundred birds within sight of land just beyond the surf zone and often within the kelp bed zone, if present. They feed by swooping down and making shallow dives into the water to snatch prey. Their principal diet includes small fish and various crustaceans, krill probably being the most important and abundant. Antarctic terns also scavenge in the intertidal zone for stranded organisms. Most terns are short-distance foragers over shoals of fish. Within a few hours, they can obtain enough fish for themselves and their chicks in the breeding colony. Many tern species forage together with other marine animals, such as porpoises or predatory fish.

Terns are normally monogamous, but in a few cases, other mating systems have been observed, including trios and female–female pairs. Most terns breed annually outside of the tropics and usually with a special annual breeding cycle. The age of first breeding varies. Only a few species breed at the age of 2 years and the first breeding age is more often 3 or 4 years. In many cases, birds have visited the colony earlier than the age of first breeding.

Most terns are colonial, sometimes they form huge colonies, and this for many years. For other species habitat changes, human disturbance, or high predation rates force birds to move the colony, sometimes during the breeding season. The density of colonies varies. Sometime birds breed only a few centimetres apart. In many cases, they defend one another against predators. The establishment of territories is the first step for males to establish or reestablish the pair bond. After a highly specialised and ritualized courtship, the males feed the females with fish, an activity often connected directly with copulation. Nest site selection takes place a few days before egg laying. Sometimes more than one scrape is made.

The clutch size varies from one to three eggs, depending on the species or on food supply. The incubation time is normally 21–28 days. Birds often start to incubate after laying the second egg. The incubation shifts vary between the sexes and among species. Hatching takes place within 1 or 2 days. Chicks are generally inactive in the first week; later they spend more time preening and walking. Normally the adults feed their chicks several times a day, mostly with only one fish on each occasion. Chicks of ground-nesting species leave the nest when they are not older than 4 days. Some species form crèches. The chick-rearing phase or fledging period is about 4 weeks. The mortality varies from species to species and from year to year. Terns are generally long-lived birds, with several species now known to live in excess of 25–30 years. An Arctic tern reached 34 years and a sooty tern 32 years.

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See also **Antarctic Peninsula; Antarctic Tern; Arctic Tern; Kerguelen Tern; Polar Front**

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TERRESTRIAL BIRDS

Land Birds of the Antarctic

The Antarctic continent is predominantly ice covered (approximately 98%); hence, there is only a small proportion of it that is exposed land. This limited ice-free habitat, combined with the harsh climate, has led to a low diversity of plants within Antarctica, and hence little or no insect fauna. Since birds need either seeds or some form of prey to forage on, there are no regularly occurring species of land birds either on the Antarctic continent or on the sub-Antarctic islands, such as the South Shetland, South Orkney, or Balleny Islands. Nevertheless, on those islands slightly to the north, land birds do occur. These islands are Île Amsterdam, the Auckland Islands, Bouvetøya, Campbell Island, Îles Crozet, Heard Island, Îles Kerguelen, Macquarie Island, the McDonald Islands, the Prince Edward Islands, and South Georgia.

Many species are either vagrants or only infrequent visitors, but there are a number of species breeding on peri-Antarctic islands. The number and variety of land birds occurring on these islands depends on the size of the islands and their proximity to other islands and to continental land masses such as South America, Africa, and Australia. The islands closest to New Zealand (Auckland Islands, Campbell Island, and Macquarie Island) have the greatest number of species breeding or occurring as vagrants. Further factors that increase the likelihood and diversity of birds on islands are their size and their latitude, with more birds present on islands farther north (where the weather is warmer and hence more benign).

Thus, in the different sectors of the Southern Ocean, certain patterns of land bird occurrence can be seen. In the Australian/New Zealand sector (Auckland Islands, Campbell Islands, and Macquarie Island), the greatest diversity is on the Auckland Islands, which are farthest north, largest, and closest to another land mass (New Zealand). Campbell Island is then closer to New Zealand and has greater diversity than Macquarie Island.

In the Indian Ocean, the Prince Edward Islands and Îles Crozet are at a similar latitude. However, the Prince Edward Islands are closer to Africa and have had a greater number of land birds recorded from them (although no breeding species, whereas Eaton's Pintail breeds on Îles Crozet).

Of these peri-Antarctic islands, eight (including island groups) are south of the Polar Front. Heard Island, Bouvetøya, and the Balleny Islands are

Distribution of terrestrial bird species

	Amsterdam, Île	Prince Edward Islands	Crozet, Îles	Heard Island	McDonald Islands	Kerguelen, Îles	Antarctic Peninsula	South Georgia	South Shetland Islands	South Orkney Islands	South Sandwich Islands	Bouvetøya	Auckland Islands	Campbell Island	Macquarie Island	Balleny Islands	No islands recorded from
Great Egret								1					1	1			3
Snowy Egret								1									1
Intermediate Egret		1															1
White-faced Heron													1	1	1		3
Cattle Egret	1		1						1	1			1	1			6
Black-crowned Night-heron	1																1
White Stork		1															1
Black-necked Swan							1		1								2
Eaton's Pintail		1	2			2											3
Yellow-billed Pintail								2	1	1							3
Speckled Teal								2									1
Blue-winged Teal								1									1
Chiloe Wigeon							1	1	1	1							4
Auckland Teal													2				1
Campbell Teal														2			1
Pacific Black Duck													2	1	2		3
Mallard													1	2	2		3
Auckland Merganser													2				1
Lake Duck									1								1
Turkey Vulture								1									1
Swamp Harrier													1	1	1		3
NZ Falcon													2				1
Peregrine Falcon	1							1									2
European Hobby	1																1
Purple Swamphen														1			1
Purple Gallinule								1									1
Allen's Gallinule								1									1
Eurasian Coot															1		1
Corncrake		1															1
Baillon's Crake															1		1
Weka															1		1
Auckland Island Rail													2				1
Eared Dove								1									1
African Cuckoo		1															1
Red-chested Cuckoo	1																1
Common Cuckoo			1														1
Pallid Cuckoo															1		1
Long-tailed Cuckoo													1				1
Shining Bronze-cuckoo													1		1		2

Barn Owl								1									1
Red-crowned Parakeet													2				1
Yellow-crowned Parakeet													2				1
White-throated Needletail														1	1		2
Fork-tailed Swift														1	1		2
Eastern Kingbird								1									1
Dark-faced Ground-tyrant								1									1
Austral Negrito									1								1
Skylark													2	1			2
Welcome Swallow													1	1	1		3
Barn Swallow		1	1						1								3
Chilean Swallow								1									1
Sand Martin		1	1														2
Northern House Martin		1															1
Yellow Wagtail		1															1
New Zealand Pipit													2	2			2
South Georgia Pipit								2									1
Red-backed Shrike		1															1
Dunnock													2	2			2
Mountain Chat		1															1
Common Blackbird													2	2			2
Song Thrush													2	2	1		3
Willow Warbler		1															1
Common Whitethroat		1															1
Auckland I. Tomtit													2				1
Silvereye													2	1	1		3
NZ Bellbird													2				1
Tui													2				1
Yellowhammer													1				1
Common Chaffinch													1	1			2
European Greenfinch														1			1
European Goldfinch													1	2	1		3
Common Redpoll													2	2	2		3
Common Waxbill	2																1
Long-tailed Meadowlark								1									1
House Sparrow			1					1					2	2			4
Starling													2	2	2		3
Species recorded	6	13	6	0	0	1	2	18	7	3	0	0	30	23	17	0	
Breeding species recorded	1	0	1	0	0	1	0	3	0	0	0	0	19	10	4	0	

Notes: 1 Species recorded visiting island
2 Species recorded breeding on the island

predominantly ice capped (and are isolated from other large land masses), and have had no land birds recorded from them. The South Sandwich Islands have significant ice-free areas, but are distant from major land masses. The McDonald Islands are small (and have been visited only twice). However, South Georgia, which is large but mostly ice covered, has had at least eighteen species of land birds recorded, including three breeding species. It is relatively close to a major land mass (1300 km from the Falkland Islands and 1700 km from South America) and has a relatively benign climate on the north coast, due to its high mountain ranges, shielding it from the full force of the westerly winds. The South Shetland Islands, while closer to South America than South Georgia is, are almost 10° of latitude farther south, and so have a much harsher climate and hence have had fewer recorded visiting birds (and no breeding land birds).

Groups of Birds Recorded

At least seventy-six species of land birds have been recorded from the sub-Antarctic islands. Of these, twenty-five species have been recorded breeding (including the now-extinct Auckland Island merganser), while the others are visitors (either vagrants or regularly occurring).

Of the twenty-five breeding species, there are a number of common groups, including eight species of ducks, nine species of introduced European birds (including a number that self-introduced from neighbouring islands, where they had initially been introduced) and eight endemic New Zealand species (including three endemic ducks). Two species of pipit also breed in these islands (the South Georgia pipit at South Georgia, and the New Zealand pipit at the Auckland Islands and Campbell Island).

The ducks include two closely related flightless ducks occurring on neighbouring islands to the south of New Zealand (the Campbell teal and the Auckland teal). The high number of New Zealand endemic birds occurring on peri-Antarctic islands is likely due to the relative proximity of the islands to New Zealand, and the number of islands in that region. The introduced European birds are yet another example of the profound effects humans have had on these islands. A number of these have become pests (while additionally, the Weka, a type of rail, was introduced to Macquarie Island, where it was a significant pest as a predator of small species of seabird).

A number of species of land birds are restricted to these peri-Antarctic islands. These are the Eaton's pintail (from Îles Kerguelen and Îles Crozet), the Auckland teal, the Campbell teal, the Auckland Island rail, the South Georgia pipit, and the Auckland Island tomtit. All species that are restricted to these islands are vulnerable due to the small size of their populations (with the population of Campbell teals estimated to be as few as 50–100 individuals) and restricted ranges, with many breeding only on single islands. They are therefore particularly vulnerable to introductions of mammalian predators, such as rats *Rattus* spp., cats *Felis catus,* and mice *Mus* spp. This vulnerability is further accentuated by the fact that these species evolved in the absence of predators, and the habitats they nest in lack trees and shrubs, so they have to nest on or near the ground.

The nonbreeding species include six species of heron, seven species of gallinule, six species of cuckoo, and five species of swallow. In addition to the eight species of duck breeding on peri-Antarctic islands, a further four species have been recorded as vagrants.

Of the species of herons, it is particularly noteworthy that three species occur on multiple islands, particularly the cattle egret, which has occurred on Île Amsterdam, Îles Crozet, the South Shetland Islands, the South Orkney Islands, the Auckland Islands, and Campbell Island, and the great egret, which has occurred on South Georgia, the Auckland Islands, and Campbell Island. These species are capable of great movements.

A number of species of gallinules also occur. In general, gallinules appear to be poor flyers. Despite this, they are capable of flying substantial distances, and occur on many of the islands of the world (including tropical, temperate, and polar islands).

Cuckoos and swallows are both groups of birds that make long-distance migrations, hence their occurrence as vagrants is perhaps not surprising. Welcome swallows have been recorded as vagrants on all groups of islands close to New Zealand, while barn swallows, a long-distance migrant, have occurred on the three different islands in the regions of Africa or South America.

TIM REID

See also **Antarctic: Definitions and Boundaries; Amsterdam Island (Île Amsterdam); Auckland Islands; Bouvetøya; Campbell Island; Crozet Islands (Îles Crozet); Heard Island and McDonald Islands; Kerguelen Islands (Îles Kerguelen); Macquarie Island; Prince Edward Islands; South Georgia; South Orkney Islands; South Shetland Islands**

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THERMOHALINE AND WIND-DRIVEN CIRCULATIONS IN THE SOUTHERN OCEAN

Hot air rises and cold water sinks—or does it? This entry explores the nature of Antarctic circumpolar convection, which is the sinking and rising motion around the continent that occurs due to changes, often subtle, in the density (mass per unit volume) of seawater, and also to the force the wind exerts on the ocean surface as it blows, steadily or in gales across its surface.

Heated air rises in a process called convection. House radiators, hot air balloons, and thunderstorms all derive from the fact that air becomes less dense when heated, therefore buoyant compared to surrounding air, and rises. The same process occurs upside-down in lakes and oceans, with cooler water sinking, and warmer water rising to take its place and remaining at the surface until cooled in turn. This usually is not observed, since it is all happening below the ocean or lake surface. However, the steam sometimes coming off relatively warm water, and the moderation of temperature extremes for a milder climate near coasts, is a result of convection and the large heat capacity of water. Why aren't the coasts of Antarctica mild? Of course, the term is relative, and they are milder than the extreme cold temperatures found further inland; the main effect of convection near the Antarctic continent, however, is not so much to warm the air as to melt the ice, whether it be sea ice offshore or glacial ice adjacent to the continent. The combination of freezing temperatures, ice, and salty seawater leads to the curious situation that the ocean surrounding Antarctica is colder at the surface than it is below the surface. This was one of the earliest observations in scientific reports from expeditions to the Southern Ocean.

Heat and Salt

Fresh water, without any salt, has the unusual property, known for over 200 years, that at near-freezing temperatures it actually reaches a maximum density at a point near 39°F or 4°C. This means that at temperatures between freezing and this point, density *increases* as temperature increases. Since the ocean is at freezing temperatures around the Antarctic continent it is natural to wonder whether this effect is relevant to Southern Ocean convection too. Early scientific explorers knew that near the continent, the temperature was colder at the surface than it was at greater depths, and reasoned that this was consistent with the fact that (fresh) water had a maximum density above freezing, hence the colder, less-dense water near freezing could float on top of the denser, warmer, deep water. It followed that there should be a zone of maximum density at some intermediate latitude between the coldest water next to the continent and warmer water as one progressed north, and that furthermore, the ocean should have this maximum density from the surface all the way to the bottom, since the water is dense and would naturally sink. Thus the existence of cold water at the surface; somewhat warmer water below, filling the depths; and yet warmer water at lower latitudes fit a consistent framework.

This was the first theory of Southern Ocean convection and the associated temperature field. That it was wrong did not stand in the way of the notion that it was reasonable, and explained some basic facts about the region. The early temperature measurements were difficult to make at sea and often only temperature maxima and minima were recorded. Salinity—the concentration of dissolved salts in seawater—affects density but was not systematically measured until much later. It is the presence of salt that not only lowers the freezing point of water (and thus salt is spread over roads to help melt ice) but also eliminates the phenomenon of a maximum density at a temperature above freezing. Seawater freezes at about 29°F, or –1.8°C, and reaches its maximum density at this point. The reason there is cold water near the freezing point at the surface is that ice is formed and melts at the surface. Where it forms, salty water is left behind and sinks, and where it melts, fresher, less-salty water is left behind and floats. In both cases the temperature is close to freezing. In general, salinity has a controlling effect on the stratification or layering of the ocean near Antarctica because, all other things being equal, the temperature tends toward the freezing point, whereas salinity is free to vary according to the ice cycle. (How salt changes the properties of water is a subject of thermodynamics.)

The sinking of the salty water or brine rejected by ice as it forms leads to the buildup of dense, relatively salty water on the continental shelf, which around Antarctica has numerous deep basins. This seasonal buildup and subsequent spilling off the shelf and down the slope into the surrounding ocean is the primary way Antarctica contributes to the global ocean convection cell, which brings relatively warm deep water south and sends cooler bottom water back north. Spilling occurs in numerous places distributed around the continent according to the geography of the continental margin and ocean circulation. As the water flows down the slope, it gathers momentum and turns left under the influence of Earth's rotation, tending to flow parallel to the coast in the westward direction. Gradually, under the influence of friction against the bottom, it sinks to greater depths and follows undersea ridges leading it away from the Antarctic continent.

There are other consequences of the salt's effect on density, or, in technical terms, the haline part of convection, as opposed to the thermal part, that play a role in heat and salt transport. If one mixes equal parts of seawater at a different temperature and salinity, but with the same density, the resulting water has a slightly greater density. This second new effect is called cabbeling, and is due to the rate at which temperature changes control density. A given change in temperature in cold water has a smaller effect on density than the same change in warm water. Hence, when the two parts of seawater mix, and the cold one is warmed and the warm one is cooled, the cold one cannot lower its density as much as the warm one can raise its density. Therefore they meet at the average temperature and salinity with a slightly greater density. This can happen within the ocean since salinity permits two water masses to have the same density despite being at different temperatures. As water moves around and comes into contact with water at the same density from a different region, they mix, producing internal convection as the mixed water sinks.

Finally, the third major heat and salt convective process, double diffusion, also depends on the interplay of temperature and salinity in the ocean. This effect arises from the fact that heat diffuses faster than salt in water. Thus, when layers of contrasting temperature and salinity form in the ocean—as they normally do because of, for example, the ice freeze-and-melt cycle or surface gradients in rainfall and evaporation—the interface between the layers can be unstable. That is to say, slight movement up or down allows the temperature to rapidly equalize with its surroundings while the salinity does not. If cold fresh water overlies warmer saltier water, as is typical in the Antarctic Zone, then heat passes into the colder upper layer and the water below becomes denser and eventually mixes; if warm salty water overlies cooler fresher water the salty layer loses heat at the interface and starts to sink. It cannot sink as a body—there must be an upward compensating motion. Rather than mixing down uniformly, however, small convective plumes form because of the intensity of the buoyancy forces on the fluid. These fingers are small enough (less than an inch wide) to exchange heat like little radiator fins with neighboring plumes, and allow the salt to be transported downward.

To put these different convective processes in perspective, consider their strength in terms of the amount of water put in motion as a result of each effect. The first process of dense water buildup by the ice freezing cycle generates on average several million cubic meters per second (one million cubic meters per second flow is called one Sverdrup and abbreviated Sv) each year of dense cold water spilling off the shelf and down the continental slope away from Antarctica, more than the flow in of all the world's rivers. These plumes of dense water, concentrated in the Ross Sea and Weddell Sea, drag surrounding water along and mix with it to produce a net flow of more than 10 Sv, by the time they leave the continental margin and enter the main part of the Southern Ocean. This bottom water eventually spreads into the major ocean basins of the Atlantic Ocean and the Pacific Ocean, filling them to the brim (that is, to the level of the sills formed by the midocean ridge) with cold Antarctic Bottom Water. Thus, early oceanographers were impressed to find cold, near-freezing water at the bottom of the ocean even at the equator, where the surface temperature can be 80°F/26°C or more.

The second process, cabbeling, is thought to generate vertical exchanges between water masses of an amount, several Sv, similar to the first, initial overflow process, but rather than reaching from the surface to the bottom of the ocean, it is restricted to relatively small steps in the interior of the ocean. Thus, its role is harder to observe, and estimates of the strength of its effect are mostly based on ocean model studies. Cabbeling is sometimes thought to work in concert with the temperature dependence of compressibility, an effect called thermobaricity. Thermobaricity means that colder water is more compressible than warmer water, so when cold water sinks its volume decreases relatively fast compared to the surrounding water, hence its density increases, giving an added push to the sinking plume. In certain special places where the stratification is weak and the temperature and salinity contrasts are strong, such as near the ocean surface, these processes can produce strong localized convection and might be responsible for maintaining ice-free zones or polynyas.

The third process, double diffusion, is primarily a means to transfer heat upward and salt downward. The associated downward shift in mass is usually neglected. This effect tends to drive an internal heat and salt transport between ocean water masses, rather than an overall convective overturning of the Southern Ocean. Evidence for double diffusion is clear so long as the appropriate temperature and salinity layering is present. It may be important to the global heat and salt balance, but its role in the Southern Ocean is still under investigation.

Deep and Shallow Convective Cells

The processes that have been described thus far are associated with a system of circulation that may be called the deep overturning circulation of the Southern Ocean, since it consists of a broad, dense, and cold outflow near the bottom balanced by flow toward Antarctica in overlying layers. This inflow takes place mainly below the level of midocean ridges. Ridges provide a boundary against which the deep currents can move with little effort, since Earth's rotation generally makes currents turn in circles if there is no boundary to support their pressure gradient. This is the situation commonly seen, for example, on weather maps of circulating high-pressure and low-pressure systems. In contrast, along mountain ranges, in the atmosphere, or on the mountain ranges of the seafloor, barrier winds and deep currents can flow long distances without being deflected. The Scotia Arc, the Kerguelen Plateau, and the midocean ridge of the Southern Ocean are examples of ocean mountain ranges along which deep currents exist.

There is another major overturning circulation called the shallow or upper circulation cell. This cell is driven strongly by the wind, which blows from west to east all around the Southern Ocean, in the descriptively named roaring forties and screaming fifties. To understand the role of the wind one must consider not just the fact that it will generate waves and drag the surface of the ocean along with it, that is, from west to east; one must also recall that the earth's rotation tends to turn the current—to the left in the southern hemisphere. The surface current is constantly dragged downwind, but the level just below is shielded somewhat from the wind and freer to feel the influence of the earth's rotation; hence, it turns to the left. And so on to deeper levels, leading to the famous Ekman spiral and the transport of water near the surface to the left of the wind in the Southern Ocean (and to the right in the northern hemisphere).

This Ekman transport is large, amounting to roughly 20 Sv when added up along a circumpolar track near 50° S. As outlined above, it flows to the left of the wind, or north, and carries Antarctic Zone properties with it, including sea ice, nutrients, and cold, less-saline surface water. These modify the water on the northern side of the Southern Ocean. To conserve mass, water must rise within the Antarctic Zone to supply this northward flow, sink in the sub-Antarctic region, and return south in subsurface layers. This constitutes the upper or shallow overturning cell of the Southern Ocean.

In the case of the upper cell, the subsurface return flow is less easily located, and several theories exist to explain the closure of the cell. The traditional view is that some of the same water that flows south along ridges as part of the deep cell upwells into the Ekman flow rather than sinking in convection zones near the continent. This is satisfying in the sense that no further explanation is required. An examination of the particular water mass layers that outcrop in the upwelling zone suggests that layers above the midocean ridges outcrop, but this poses a problem since some sort of boundary is needed to permit north–south flow in the Southern Ocean, as described previously. The problem can be reconciled by the turbulent nature of fluid motion, which allows for turbulent transports of mass (and heat and salt and other properties) in layers that are not bounded by ridges. This occurs in much the same way that surface waves, which appear to pass by floating objects without causing any net motion, can actually generate significant mean flows or net displacements of objects on the surface if they are large enough.

Among the strongest components of turbulence in the ocean are vortices, often called eddies. They are the swirls one sees in images of the surface temperature or ocean chlorophyll color, and they can be tens to hundreds of miles or kilometers across. They are common in the Southern Ocean because the strong Antarctic Circumpolar Current spawns them to lose some of the energy put in by the wind and focused by bathymetry. They are implicated in the process of closing the upper cell, returning part of the water carried north in the Ekman flow. Some theories even have them canceling part of the Ekman flow itself, saving them from the problem of returning it south at deeper levels. At present, estimates of the overturning circulation in the upper and deep circulation cells from available observations suggests that the lower cell is a bit stronger, at about 17 Sv, than the upper cell, at about 14 Sv. Acting in combination, these two cells carry about 24 Sv of deep water to the Southern Ocean from the rest of the World Ocean farther north, and provide a compensating outflow near the bottom and in the surface layer.

Variability

The picture of upper and lower convection cells, with sea-ice formation and brine rejection, plumes spilling off the shelf, and Ekman transports, is not a static one; it shows variability at many time scales. The most important of these is of course the seasonal cycle. Within the seasonal cycle there are periods of warmer or colder days, stronger or weaker winds, a good example being the occurrence of katabatic wind events. These are the strongest source of variability at the surface near the continent. Farther offshore, storms drive variability in the low-pressure belt centered near 65° S, and affect Ekman transports in a complicated fashion as they grow and decay in their circumpolar course.

Recent research has synthesized some of this variability into what are called large-scale modes of variability. Analyses show that one mode, called the Southern Annular Mode for its roughly circularly symmetric appearance, dominates the wind variability at large scales. This mode can vary rapidly in time, as rapidly as 1 week or so, but also shows longer period phases of activity. It represents the expansion and contraction toward the South Pole of the high-latitude component of the atmospheric jet stream system that rings the Southern Hemisphere near 50° S. The role of this mode in the development of the various convective elements described previously is just now starting to be revealed.

At longer than seasonal time scales, over periods greater than 1 year, say, another mode of variability with a large impact appears to be the El Niño–Southern Oscillation mode. This mode derives from tropical temperature anomalies and produces the well-known El Niño phenomenon. El Niño reaches as far as the Southern Ocean, in the southeastern Pacific, because large-scale atmospheric waves propagate from the tropics to higher latitudes and modify the wind pattern. This also modifies sea-surface temperatures and the movement of fields of sea ice. El Niño is thought to have an irregular period of recurrence of 4–7 years. At longer time scales, the question of which mode of variability is most important remains open.

Ecosystems

There is also a relationship between thermohaline and wind-driven modes of convection and biology, shown in the long-established research on coastal and equatorial upwelling, the flux of nutrients into the sunlit levels of the upper ocean, and the consequent productivity. In the Southern Ocean, the upwelling extends over vast interior areas of the ocean, and other mechanisms of upper-ocean mixing, including eddy transports, may play a role as well. Closer to the continent, communities of organisms live in sea ice, so processes that influence the distribution and amount of sea ice will have an impact on this part of the ecosystem. Both the upwelling of warmer water and Ekman transport exert some control on sea ice in this context.

The larger-scale modes of variability also have an impact on ecosystems through the control they exert on broad-scale upwelling and upper-ocean physics. Modern observational techniques such as remote sensing by satellites are giving us opportunities to find the links between physics and biology at the largest scales in the ocean surrounding Antarctica.

Conclusion

The rich dynamics of the ocean circulation permit many physical processes to interact, interfere, or coexist. These processes produce exchanges between different components of the ocean atmosphere–ice system and create links that are important for weather, climate, and living organisms. Observational, analytical, and numerical studies are helping to sort out the dominant processes at work in the Southern Ocean.

This scientific sorting process is important for a number of reasons, not the least of which is to satisfy curiosity about nature and about natural cycles of the Earth system. But another reason of growing importance is the pressing need to develop climate models up to the task of predicting the consequences of human-induced global change. What is not yet known is how to quantify the net effect of large-scale turbulence and many small-scale phenomena into a formula that depends only on more easily observable quantities, like the wind forcing and surface properties. When these are developed and tested it will be possible to make better climate forecasts.

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See also **Antarctic Bottom Water; Circumpolar Current, Antarctic; Circumpolar Deep Water; Eddies in the Southern Ocean; Southern Ocean: Bathymetry; Southern Ocean Circulation: Modeling; Southern Ocean: Climate Change and Variability; Southern Ocean: Vertical Structure**

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THWAITES AND PINE ISLAND GLACIER BASINS

Thwaites and Pine Island glaciers occupy a central role in the stability and evolution of the West Antarctic Ice Sheet. They spread between 100° and 110° E and 75° and 81° S, and drain 390,000 km^2 of ice into the Amundsen Sea, South Pacific. They are the fastest-flowing glaciers in the Antarctic and the largest dischargers of ice into the ocean. More importantly, they are grounded on bedrock several kilometers below sea level, which deepens towards the interior. This configuration makes them prone to rapid retreat and they are designated "the weak underbelly of West Antarctica." Their divide overlays Bentley Subglacial Trench, a trough 1500 m below sea level that connects the Ross ice streams, Thwaites/Pine Island, and the Ronne ice streams. Retreat of the grounding line of Thwaites and Pine Island glaciers into Bentley's trench would shrink the drainage area of the Ross and Ronne ice streams, thereby affecting the entire West Antarctic Ice Sheet. Despite its importance, few observations of this sector have been gathered due to its heavy sea-ice cover, the harshness of its weather, and its remoteness from manned stations.

Pine Island glacier was discovered in 1947 from the USS *Pine Island* during Operation Highjump. It is a 30-km-wide, 400-km-long confined glacier, with an unusually bow-shaped catchment basin of 165,000 km^2 that flows at 3 km per year into a 60-km-long floating ice shelf. Thwaites Glacier, directly to the west, is much wider (110 km) and drains an oblong-shaped basin of 180,000 km^2. Thwaites Glacier comprises a 50-km-wide fast trunk on its western flank that flows at 2.5 km per year into a protruding, unconfined ice tongue subject to multidecadal calving, and an eastern flank slowly moving (500 m per year) into a fractured, mottled ice shelf buttressed by ice rises. Satellite Interferometric Synthetic Aperture Radar and radar altimetry indicate that the two glaciers result from the merging of many (8–10) tributaries, several hundred kilometers inland, which is an unusual characteristic compared to other Antarctic glaciers. Seafloor bathymetry in Pine Island Bay shows that Thwaites and Pine Island glaciers used to coalesce to form one giant ice stream, with deeply incised meltwater subglacial channels, that reached the edge of the continental shelf at the last glacial maximum.

Snow accumulation is high compared to the rest of Antarctica, about 35–50 cm water equivalent per year. This high precipitation results from synoptic-scale cyclones travelling around the Antarctic and coming ashore at the Amundsen Sea where the circumpolar trough is the deepest. The area is dotted with many emerging rocks and mountains, most of which are volcanoes.

Oceanographic data show that the glacier floating sections bathe in warm circumpolar deep water that intrudes onto the continental shelf and generates the highest bottom melt rates yet measured in Antarctica, about 50 m per year near the line of grounding of the glaciers. This means that two-thirds of the glacier ice melts into the ocean before it reaches the ice front and calves into large, tabular icebergs.

Until the 1990s, the few available observations of Thwaites/Pine Island glaciers suggested a gain in mass, which was contradictory to a collapse. Observations from the ERS-1/2 radar satellites, however, revealed that the glacier grounding lines, where ice meets the ocean and becomes afloat, are retreating fast (1 km per year), ice elevations are dropping meters per year, and ice discharge has been accelerating 1% per year over the last 30 years. This situation is not unique and affects neighboring glaciers Haynes, Smith, Pope, and Kohler as well. Yet no other sector of continental Antarctica is changing as fast as the Amundsen Sea sector. Ice thinning and ice flow are strongly correlated, which means that mass losses are not caused by changes in precipitation but by dynamic strain-thinning of the glaciers, i.e., accelerated flow.

Total discharge from the Amundsen Sea Sector is 241,000 km^3 ice per year. This volume of ice exceeds total snow accumulation in the catchment basin by 60%. Hence, the glaciers are losing mass to the ocean. They contribute more than a 0.25 mm to global sea-level rise per year at present. If all ice contained in their catchment basin were to melt into the ocean, global sea level would rise by more than one meter.

The glacial history and evolution of Thwaites and Pine Island glaciers are not fully understood at present, so one can only speculate about the future. The flow acceleration and thinning are attributed to the strong melting of the floating ice shelves by a warm ocean. Ice-shelf melting and grounding-line retreat reduce the buttressing force of ice shelves on grounded ice, thereby allowing faster rates of ice discharge than required to maintain equilibrium with snow accumulation in the interior. The zones directly upstream of the grounding lines are only slightly grounded, a few tens of meters above hydrostatic equilibrium, and named ice plains. At the current rate of ice thinning, these ice plains will soon become afloat and allow faster rates of ice discharge. The glaciers may then retreat into deeper ice, and the process may accelerate, become irreversible, and lead to the demise of ice over the entire basin. Continuous observation of this sector of West Antarctica is therefore of great relevance to the future of the West Antarctic Ice Sheet in a warming climate, with potential impacts at the global scale.

Eric Rignot

See also **Antarctic Ice Sheet: Definitions and Description; CryoSat; Filchner-Ronne Ice Shelf; Glacial Geology; Glaciers and Ice Streams; Ice–Rock Interface; Ice Sheet Mass Balance; Ice Sheet Modeling; Ice Shelves; Icebergs; ICESat; Lambert Glacier/Amery Ice Shelf; Larsen Ice Shelf; Ross Ice Shelf**

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TIDES AND WAVES

Waves are the fairly regular motions associated with the transmission of energy through the ocean. Familiar examples are surface waves caused by the local wind ("wind waves") and by distant storms ("swell"). The tide, which is a type of wave, is the regular rise and fall of the ocean surface caused by the gravitational forces of the moon and sun acting on the earth and its ocean. The ocean's vertical stratification (less-dense surface water overlying denser deep water) sets the scene for another type of wave called a baroclinic (or "internal") tide. These and other waves influence the Antarctic oceans, sea ice, floating ice shelves, and the adjacent grounded ice streams and plains. Tides are produced by the difference in the gravitational attraction of the moon (and sun) between the earth's surface and its center of mass. The complex geometry of the orbits and rotation of the sun–earth–moon system creates complex time variation in forcing. This forcing is, nevertheless, easily represented as the sum of many tidal "harmonics," where each harmonic is a sine wave of known frequency.

The main tidal harmonics are divided into two species. Semidiurnal tides have periods that are semidiurnal (roughly 12 h, and more energetic), while diurnal tides have periods of about 24 h. Most locations on the earth experience semidiurnal tides (two high tides per day), since the tide-generating forces are stronger for M_2 and S_2 than for K_1 and O_1. In many regions, however, there is a pronounced difference between the two high or low tides; these are "mixed" tides. In some regions the tides are diurnal (one high tide per day). The superposition of many tidal harmonics leads to tidal variation with a fortnightly cycle. The largest and smallest tides during this period are called "spring" and "neap" tides. Long time-series also contain variability at fortnightly, monthly, semiannual, and annual periods, and an 18.6-year-period "lunar node" tide can be found in extremely long records.

Tides are semidiurnal in the Weddell Sea but are predominantly diurnal in the Ross Sea. Statistics of tide height and velocity fields from a tide model show that the largest tide heights are in the Weddell Sea under the Filchner, Ronne, and Larsen Ice Shelves. The tidal range in these regions can exceed 5 m at spring tides. Moderate tides are also found along the Siple Coast under the eastern Ross Ice Shelf. The tide heights elsewhere around Antarctica are smaller, with a typical spring tidal range of 1.5–2 m. Tidal currents range from negligible to greater than 1 m s^{-1} at spring tides. The largest currents are along the edge of the continental shelf in the northwest Ross Sea, and under the northern edge of the Ronne Ice Shelf in the southwestern Weddell Sea. Our knowledge of tidal variability around Antarctica comes from two sources: recorded time-series of ocean height and currents, and tide models. Compared with coastal regions of populated continents, tide height records around Antarctica are sparse. Most coastal tide gauges are near manned bases, and most of these are along the coast and islands of the Antarctic Peninsula. Several time-series of ice-shelf elevation were obtained with gravimeters on the Ross Ice Shelf in the 1970s. A few more-accurate and longer-duration records are now available from bottom pressure recorders. Sources of Antarctic tide-height information include measurements of the surface elevation of both the ocean and ice shelves using satellite radar and laser sensors, and geodetic positioning system (GPS) measurements from ice shelves. Current meters deployed on moorings provide information on tidal velocities. Hundreds of current meter records have now been retrieved from Antarctic seas, including meters placed under the Ronne Ice Shelf by the British Antarctic Survey.

Most practical applications require that tide height or currents be predicted from models. The simplest models are based on analyses of time-series of elevation or velocity. The amplitude and phase coefficients for each of the tidal harmonics in the time series are calculated, and these coefficients are then recombined to predict height or velocity at other times. These predictions can be very accurate, especially for elevation, but only work near where data have been obtained. A better view of the spatial variability of tides comes from numerical models, which are solutions to the equations of fluid motion for a system forced by the gravitational attraction of the moon and sun, and with specified conditions at the model's ocean and coastal boundaries. There are several sources of error in these models, including uncertainties in the location of ice-shelf grounding lines (where glacial ice flowing off the continent first starts to float), open-ocean bathymetry and water-column thickness under the ice shelves, and model simplifications required for computational speed. Nevertheless, recent models are sufficiently accurate to be useful for assessing the role of tides in Antarctic glaciology and oceanography.

Tidal influence on Antarctic geophysical processes begins on the landward side of the grounding line and extends seaward into the deep water north of the continental shelf break. Data from GPS receivers mounted on grounded ice show that the rate of seaward flow of ice streams can be modulated by the ocean tide. For example, east of the Ross Ice Shelf, ice that remains stationary most of the time maintains a net seaward flow by rapid "slip" events, each only a few minutes long, occurring exactly twice per diurnal tidal cycle. A few kilometers offshore from the grounding line, ice shelves float freely on the ocean surface as it rises and falls with the tide. The flexure of the ice between the grounding line and the free-floating shelf forms crevasses that can pose navigational challenges to people trying to cross these regions. The tide's large contribution to ice-shelf surface elevation complicates the interpretation of satellite remote-sensing data sets used to monitor long-term changes in ice shelves.

Underneath ice shelves, tides are the primary source of ocean velocity, and turbulence caused by these currents moving against the ice contributes to the rate at which ice melts. Basal melting is one of the main processes by which ice is lost from the Antarctic Ice Sheet, the other major source being iceberg calving. Basal melting occurs when the temperature of ocean water in contact with the ice is higher than the local freezing point. If the ocean is not turbulent, melting ice creates a stable layer of relatively fresh, cold water directly below the ice, insulating it from further melting. Tide-driven turbulence can overcome this stabilization, with strong tidal currents under the front of the Ronne Ice Shelf contributing to melt rates exceeding 2 m of ice per year.

North of the ice shelves, the primary role of tides comes from mixing driven by friction at the seabed, and by the transfer of energy from the "barotropic" to the "baroclinic" tide. The barotropic tidal current is the current that results directly from the gravitational forces of the moon and sun. This current is fairly constant with depth. The baroclinic tidal current has more vertical structure, and exists because the ocean density varies with depth. Barotropic currents are important in polar oceanography because they increase the friction at the seabed, causing more mixing than would be found if there were no tides. This mixing affects the characteristics of the water masses, including the cold, dense Antarctic Bottom Water that is formed around Antarctica and contributes to the deep circulation of the world's oceans. Baroclinic tides are created when barotropic tidal currents flow across steep and/or rough topography, and, if large, can contribute to ocean mixing. Whereas barotropic tides cause most mixing near the seabed or at the base of land-fast sea ice and ice shelves, baroclinic tides can create mixing in the interior of the water column, away from boundaries. Thus, baroclinic tides can contribute to the mixing of water masses at intermediate depths in the ocean. Baroclinic tides in the Southern Ocean are usually weak because density differences between surface and deep waters there tend to be small. Exceptions occur near "critical latitudes," where the tidal period equals the local inertial period.

Tidal currents also apply a force to the base of the ice. Drift tracks of buoys that have been deployed on sea-ice floes show that the ice moves with the tidal currents, although not always at the same speed. Spatial gradients of the tidal forcing can cause the ice floes to diverge and converge at tidal periods. While a solid cover of thick sea ice is a very effective insulator, the temporary open-water fractures ("leads") created by the tides weaken this insulation, causing an increase in heat exchange between the ocean and atmosphere and leading to more sea-ice formation than would occur if tides were absent. Recent numerical modeling of barotropic tidal currents suggests that these leads can increase area-averaged heat-loss and ice-formation rates in winter by about 50% in parts of the western Weddell Sea. When baroclinic tides are present, the mean fraction of open water due to tides may be further increased.

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See also **Antarctic Bottom Water; Coastal Ocean Currents; Glaciers and Ice Streams; Ice Shelves; Sea Ice: Types and Formation; Southern Ocean: Bathymetry; Southern Ocean Circulation: Modeling; Southern Ocean: Vertical Structure**

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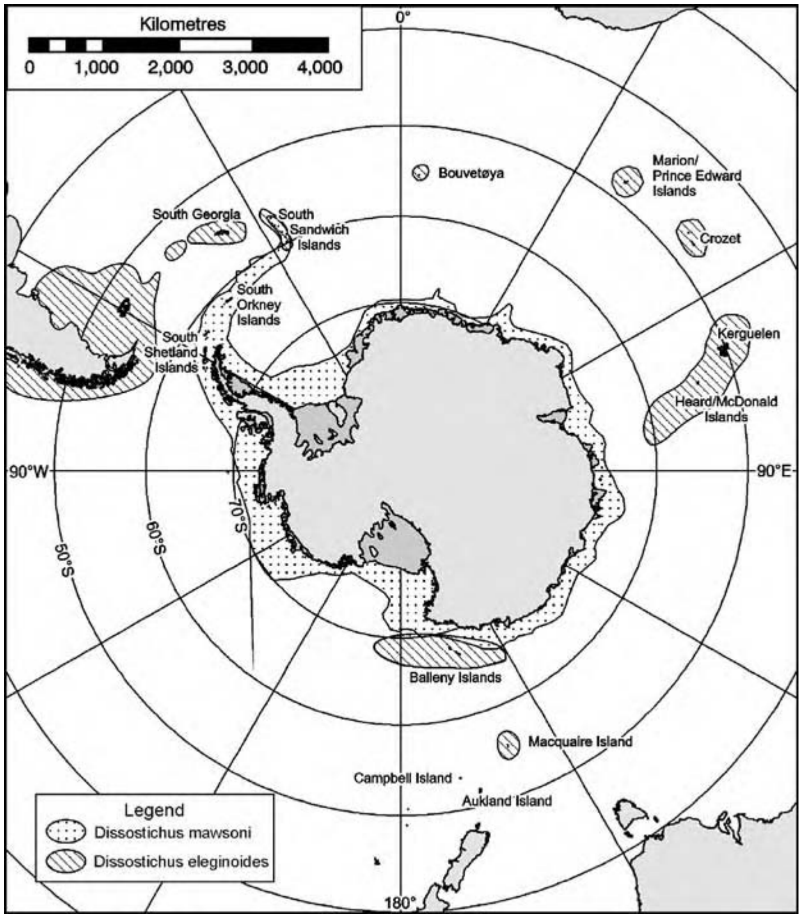
TOOTHFISH

Toothfish, named for the sharp teeth on the upper jaw, belong to the genus *Dissostichus* in the family Nototheniidae (Antarctic cods), which are endemic to the Southern Hemisphere and dominate Antarctic fish assemblages. There are two species of toothfish: the Antarctic toothfish *(Dissostichus mawsoni)* is found at high latitudes around Antarctica, whilst the Patagonian toothfish *(Dissostichus eleginoides)* occurs farther north around sub-Antarctic islands such as South Georgia and around the southern tip of South America. There is some overlap in their distribution in intermediate areas. Both species grow to large sizes, reaching lengths in excess of 2 m and weights greater than 100 kg, and can be distinguished by the pale edge of the caudal and pectoral fins and the longer lower lateral line in *D. eleginoides*.

Toothfish are active predators and scavengers, occupying a broad depth range, but the biology and ecology, particularly of the Antarctic toothfish, are poorly known. Juvenile fish generally occur in shallow water, with the mean size of fish increasing with increasing depth, to a maximum depth in excess of 2000 m. Toothfish are believed to spawn in deep water (500–1000 m), with the main spawning period around South Georgia probably in the austral winter (Agnew et al. 1999). Females produce between 50,000 and 500,000 relatively large (4–5 mm) pelagic eggs that hatch into small pelagic larvae. The duration of the pelagic larval stage is not known, but by the time fish have reached 200 mm in length they are found associated with the sea floor at depths of 100–200 m.

Growth rings from scales and otoliths (ear stones), which record seasonally alternating periods of rapid and slow growth, have been used to estimate the age of toothfish (Horn 2002). These studies suggest that, in contrast to other deep-sea fish, toothfish grow reasonably quickly for the first 10 years, reaching up to 1 m in length. As the fish grow there is a gradual migration to deep water, with an associated change in diet, and although large fish are still caught in shallow water, they are most abundant at depths of 750–1500 m. After the initial, relatively rapid growth, toothfish reach maturity and subsequent growth is slower. The reduced growth may be associated with an annual investment of energy in reproduction, but also with the reduced availability of food in the deep



The distribution of the two species of toothfish. The distribution of *Dissostichus mawsoni* has been inferred from catch records and extrapolation to the 2000 m depth contour.

sea. Females generally grow faster and reach a larger size than males with maximum longevity in both sexes of up to 50 years (Horn 2002).

Juvenile toothfish are essentially visual predators and use their sharp teeth to catch the fish, crustaceans, and cephalopods that make up a considerable portion of their diet. As the growing fish migrate deeper, light levels decline and toothfish probably rely less on vision and more on alternative senses such as olfaction and mechanoreceptors in their lateral lines, which detect movement and sound. The diet changes accordingly and larger, deep-living toothfish will scavenge carrion (such as dead fish and squid) that falls to the sea floor, to supplement their diet of benthic fish and decapod crustaceans (Arkhipkin et al. 2003; Collins et al. 1999; Pilling et al. 2001). Large toothfish probably have few predators, particularly when they are in deep waters, but juveniles have been reported in the diets of penguins, sea lions, sperm whales, and elephant seals.

In addition to the bathymetric migrations, there is evidence that toothfish undertake local, small-scale movements, probably related to feeding and reproduction. However, despite their large size, the results from tagging studies suggest that adults do not undertake large-scale migrations (Williams et al. 2002). The single incidence of a toothfish being caught in the North Atlantic (Moller et al. 2003) is dubious and deep ocean basins probably present a physical barrier to migration between distant populations. Genetic studies suggest that geographically distant populations of toothfish are separate stocks (e.g., Shaw et al. in press), with a major genetic break between populations of Patagonian toothfish found in the Southern Ocean and those on the South American Plateau. Within the Southern Ocean there are genetic differences between the isolated populations of the sub-Antarctic islands, which suggests that each small, localised population is a separate stock.

Patagonian toothfish are a major target for commercial fishermen, and the high value of the catch has attracted pirate vessels to the Southern Ocean. The fishery began in the late 1970s, when juvenile toothfish were caught by trawlers as a bycatch in shallow-water fisheries around South Georgia. In the late 1980s, a targeted longline fishery for larger adults began in Chilean waters, but rapidly spread to the Patagonian shelf, and sub-Antarctic islands. The FAO-reported landings of Patagonian toothfish increased from less than 5000 tonnes in 1984 to 40,000 tonnes in 1992. The expansion of the fishery caused concern about overexploitation and the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), which is responsible for managing resources in Antarctic waters, sought to control the expansion of the fishery in its area of jurisdiction by setting precautionary catch limits. Unfortunately, the value of the catch and the difficulties of enforcing regulations in such a large and inhospitable ocean led to the development of significant illegal fishing in the mid-1990s, which had a detrimental effect on the toothfish stocks as well as causing large-scale mortality of seabirds. On a more positive note, the recent introduction by CCAMLR of a catch documentation scheme, which means that legally taken fish can be traced to supermarkets, and the high-profile arrests of pirate vessels have reduced the take by illegal vessels. An experimental fishery for Antarctic toothfish has recently started in the Ross Sea.

The longline fishery operates in deep waters (700–1500 m) where the large adults are most abundant and are readily attracted to hooks baited with squid or fish (Agnew 2004). Long-lining is a more selective fishing method than trawling, generally only catching scavenging fish and doing less damage to the sea floor and its associated fauna. In the toothfish fishery at South Georgia, there is a small bycatch of skates, grenadiers, and deepwater hake, but problems with the incidental mortality of seabirds, particularly albatrosses, have caused greater concern. When the baited hooks are deployed from the stern of the long-lining vessels, many seabirds, including albatrosses and petrels, are attracted. In attempting to take the bait they become caught on the hooks and drown when the hooks sink. Incidental seabird mortality was initially a problem with the toothfish fishery, but this has been addressed by CCAMLR, and mitigation measures to keep birds away from baited hooks have almost eliminated seabird catches.

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See also **Albatrosses: Overview; Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Fish: Overview; Fisheries and Management; Larvae; South Georgia**

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TOURISM

During the past 50 years, Antarctica and its neighbouring island groups have become tourist venues. The first sightseeing tourist aircraft overflew the Antarctic Peninsula from South America in December 1956; the first shipload of paying passengers followed a similar route in January 1958. Since then both airborne and ship-borne tourism to Antarctica have increased radically. In the summer of 2003–2004, almost 25,000 tourists were estimated to have visited the area by air or sea, some 20,000 of whom landed on the continent or nearby islands. These numbers are tiny compared with those visiting other tourist attractions worldwide, but remarkable for a continent that, up to 50 years ago, was visited almost exclusively by explorers, scientists, and their support staff. Antarctica's main attractions for tourists are spectacular scenery and natural history, followed closely by the history of exploration (exemplified by historic huts), and evidence of current research activities, especially visits to working stations. Relatively few visit for climbing, skiing, or trekking to the remoter parts of the continent.

Ship-Borne Tourism

The most popular area for ship-borne visits remains the South American sector—the South Shetland and South Orkney Islands and Antarctic Peninsula, which lie within 1 or 2 days' sailing from the ports of Ushuaia (Argentina), Punta Arenas (Chile), and Stanley (Falkland Islands). The sub-Antarctic island of South Georgia lies some 3 to 4 days' sailing from these ports. To reach other areas of mainland Antarctica, for example, historically interesting McMurdo Sound, Cape Adare, and Commonwealth Bay, requires voyages two to three times longer, mainly from Hobart (Australia) or Lyttleton (port of Christchurch, New Zealand), across wider stretches of the world's least hospitable ocean. Macquarie Island and the southern islands of New Zealand are often included in these itineraries.

In January and February 1958, *Les Eclaireurs,* an Argentine naval transport, carried one hundred paying passengers to the Antarctic Peninsula in each of two voyages. In the following season, both Chilean and Argentine government ships made similar voyages, between them carrying over three hundred passengers. The first cruise dedicated solely to tourism occurred in 1966, when Lars-Eric Lindblad, an entrepreneur of worldwide adventure travel, chartered the Argentine naval vessel *Lapataia* for fifty-eight passengers on a voyage to the Antarctic Peninsula. In 1967, Lindblad promoted two further cruises, again to the peninsula, and in 1968 he arranged for two voyages to the peninsula in the Chilean transport *Navarino* and two to the Ross Sea region in the Danish ice-strengthened ship *Magga Dan*. So began regular summer cruises to Antarctica, and the establishment of the benign "Lindblad pattern" of tourist management that has since permeated the whole of the industry. In the following decades, Antarctic ship-borne tourism grew erratically but surely, involving more ships making more voyages and carrying more passengers each year.

Typically visits are made between mid-November and mid-March, when weather and ice conditions are best, and wildlife is most spectacular. Visits that promise landings are necessarily restricted to readily accessible parts of the coast. Most of the ships involved alternate visits to Antarctica with voyages in warmer waters and the Arctic. Passenger numbers per ship range from fewer than fifty to seven hundred or more, though operators who land passengers restrict numbers to five hundred or fewer. Some ships are ice-strengthened; two or three with ice-breaking capacity can take their passengers on more adventurous cruises into the pack ice.

Some indication of the industry's growth can be gained from statistics provided annually by the US National Science Foundation and International Association of Antarctica Tour Operators (IAATO). In the 1992–1993 season, twelve ships made a total of sixty-three voyages, landing almost seven thousand passengers. In 2003–2004, 29 ships made a total of 168 voyages, landing over 19,000 passengers. Within the past 5 years a few larger liners with the capacity for 1000 or more passengers have visited the peninsula area each season, without attempting landings. In 2003–2004, three "big" ships made five cruises, carrying over 4900 visitors. At the other end of the scale, a few privately owned and chartered yachts, some with paying passengers, appear in Antarctica each year. Most are summer visitors; a few remain over winter. Paying passengers continue to be carried on naval transports and other expedition ships, usually in less luxury though more cheaply than on scheduled cruises.

Under Antarctic Treaty regulations, operators and masters of tour ships are licenced by their governments and provided with regulations and guidance that outline the ground rules for taking parties ashore, and the location and extent of protected areas (which for practical reasons are seldom marked in the field). A strong duty is imposed on them to ensure the good behaviour of both passengers and crew, ashore and afloat. Except in areas set aside for scientific research or strict conservation, and in the immediate environs of active stations, operators are free to land passengers virtually anywhere. In practice, ships use a limited number of sites that are recognized for their intrinsic interest and safety of operation. Over 270 such sites have been identified in the Antarctic Treaty area, though of these only about half are visited in any one year. The dozen most popular sites may be visited every second or third day throughout the season; some have now been visited regularly for over 40 years.

Fortunately for these areas (which some ecologists regard as particularly fragile), Antarctic tourism is dominated by a strong ethic of environmental concern and conservation, based largely on Lindblad's management concept, which many of today's cruise directors and expedition leaders continue to follow. Lindblad also cofounded IAATO, an organization that since 1991 has promoted safe and environmentally responsible private-sector travel, and represented the industry in dealings with the Antarctic Treaty System, its ultimate governing body. IAATO produces codes of conduct and other guidelines and recommendations for members and clients that have formed the basis of legislation under the Treaty System.

Typical small Antarctic cruise ships carry 100–140 passengers, operating under an experienced captain and cruise leader. Each voyage is treated as an adventure expedition, with shipboard lectures, briefings, and one or more daily landings. Lecturing staff are themselves often experienced Antarctic researchers or administrators. Landing sites are selected by expedition leaders for their historical associations, natural history (penguin colonies are particularly favoured), scenic beauty, or other qualities. Before their first landing passengers are briefed on the requirements of the Antarctic Treaty covering visitors, and issued with a set of treaty-based guidelines that cover their behaviour ashore, possible hazards, the need to avoid interference with wildlife, and other points of conduct. Landed by inflatable boats in parties of ten to fifteen, the passengers are helped ashore, accompanied, and supervised by well-informed guides. For safety reasons, and to ensure satisfactory guide-to-passenger ratios, ships avoid having more than about one hundred passengers ashore at a time.

Visitors wear gumboots, which they are required to wash before and after landings, and are usually provided with bright padded jackets, to ensure that they can be seen from a distance. They are usually free to wander from their parties, but required to keep off glaciers, avoid climbing and other hazardous pursuits, avoid harassing animals or damaging plants, and stay within sight and easy reach of the embarkation point. Visitors who drop litter, knowingly trample vegetation, or interfere seriously with wildlife are likely to be reminded of their responsibilities by their guides, or more often by fellow passengers. Parties remain ashore for 1–3 hours, moving within a radius of few hundred metres, seeking photo opportunities and watching wildlife.

There may be up to three such landings per day, interspersed with prearranged visits to scientific stations, or to abandoned bases, whaling stations, and historic monuments, or hour-long scenic boat tours among icebergs and islands. Evenings before dinner are usually taken up with a "recap" session, in which the day's events are discussed, and plans for the following day announced. This is often the occasion for cruise leaders and staff to reinforce the expedition spirit, and reiterate the conservation ethic that all the well-organized tours actively promulgate.

The "Lindblad pattern" of management continues to be favoured, at least in principle, by most operators, but is challenged by fundamental changes in a developing industry. Its most serious challenge appears in ships carrying more than 150 passengers, which for economic reasons are likely to become the majority in the future. Larger, more heterogeneous communities of passengers are likely to include wider age ranges and more diverse backgrounds than the mainly retired clientele to whom Lindblad catered. They may not all accept without question the same underlying conservation ethic. They are likely to include several language groups, which need to be addressed separately. Bigger ships offer alternative forms of entertainment, from bingo to dancing troupes. Two sittings for dinner make it impossible for all the passengers to meet in one place at one time, and share their experiences each evening with the cruise director and staff. Younger age groups demand more active participation than the pattern allows. Forward-looking operators meet these challenges by finding alternative management methods for the larger numbers and greater diversity of passengers who make up the modern clientele.

Airborne Tourism

The pioneering overflights of 1956 from South America were repeated irregularly during the following years. From February 1976, Boeing 747s from Australia and DC-10s from New Zealand carried several thousands of passengers in flights over the East Antarctic mainland. These ended on 28 November 1979 when a low-flying New Zealand aircraft crashed on the slopes of Mount Erebus, Victoria Land, with the loss of 257 passengers and crew. Flights from Australia resumed in 1995 and continue to prove popular.

In 1979–1980, the Chilean government installed a 1300-m-long hard runway and a hostel for visitors at Teniente Rodolfo Marsh Station, King George Island, South Shetland Islands, making possible tourist flights with landings from Punta Arenas. These gave passengers the choice of returning the same day, staying briefly on King George Island for walks or helicopter flights, or joining tour ships for cruises of the Antarctic Peninsula. Marsh Station continues to be used in this way: two other hard runways have been developed in the Peninsula area and may become available as the industry expands. However, bare-ice patches in the interior of Antarctica are also being used as runways for wheeled aircraft, making possible a much wider range of tourist flights. Adventure

Network International, for example, flies exploring parties, camera crews, and climbers, trekkers, ornithologists, and other kinds of tourists from southern Chile to the Patriot Hills, Vinson Massif (Antarctica's highest peak) in the Ellsworth Mountains, the South Pole, and other remote corners of Antarctica. Supporting both national and private expeditions, this and similar enterprises are opening virtually the whole of Antarctica to airborne tourism. The main factor limiting expansion is the high cost of safe and ecologically sound operations, currently restricting uptake to a few dozen passengers per year.

Regulation of Tourism

Tour operators and their clients whose governments are signatories to the Antarctic Treaty are responsible for their activities under the Protocol on Environmental Protection. This requires the same degrees of accountability that applies to scientists, support staff, and all other visitors to Antarctica. In the absence of any form of policing or ranger control, more stringent regulations would not at present be practicable. Fortunately most operators find it advantageous to join IAATO and subscribe to its precepts, so the industry remains effectively, and on the whole benignly, self regulating. In addition, the Antarctic Treaty Consultative Parties are now taking a more direct interventionist role with the development of site guidelines to provide agreed-upon control mechanisms for the most visited sites.

The first half-century of Antarctic tourism has provided little evidence of environmental damage, and far fewer permanent changes to the environment than have been effected by scientific research or politically motivated activities. There would therefore be little to justify more rigorous controls. However, the industry continues to grow, entirely in response to market demands, with no controlling authority licensed, financed, or willing to impose restrictions should they later be judged necessary.

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See also **Antarctic Peninsula; Antarctic Treaty; Archaeology, Historic; Aviation, History of; King George Island; Penguins: Overview; Protocol on Environmental Protection to the Antarctic Treaty; Seals: Overview**

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TRANSANTARCTIC MOUNTAINS, GEOLOGY OF

The Transantarctic Mountains (TAM) are one of the earth's great mountain belts. They extend over 3500 km from the Oates Coast and northern Victoria Land areas of the Australia–New Zealand sector, to the Pensacola and Shackleton ranges along the eastern Ronne Ice Shelf. Although geographically separate, Paleozoic and Mesozoic rocks in the Ellsworth Mountains correlate with TAM geology. Physiographically they represent a major divide between East and West Antarctica, rising to elevations of more than 4000 m (>14,000 feet) directly from sea level along the Ross Sea coastline. Vinson Massif in the Ellsworth Mountains is the highest point in Antarctica (5140 m). Antarctica today is largely surrounded by passive margins and spreading centers, but the TAM represent a significant intraplate mountain belt with a long history of events marking the tectonic evolution of West and East Antarctica. To the east, the TAM are flanked by igneous and metamorphic rocks of the Precambrian East Antarctic craton, although these rocks are mostly ice covered and known from scattered coastal outcrops and geophysical surveys. Westward, along the margin of the Ross Sea and in Marie Byrd Land, the TAM are bounded by heterogeneous crust of West Antarctica, composed primarily of Paleozoic and Mesozoic sedimentary and igneous rocks, as well as Cenozoic volcanics. Present-day topographic expression in the TAM is related to geologically recent extension along the Ross Sea margin, yet rocks exposed in the range reflect a protracted history of continental rifting, mountain building, and renewed crustal extension between late Precambrian and Mesozoic time.

Sailing expeditions crossing from the southern Pacific Ocean first sighted high peaks of the TAM in the mid-nineteenth century, and the region was named Victoria Land by the British Antarctic (*Erebus* and *Terror*) expedition (1839–1843) under James Clark Ross. A later British expedition (1898–1900) led by Carsten E. Borchgrevink made landings between northern Victoria Land and Ross Island, sampling volcanic rocks in the region.

The first geological studies to penetrate inland in the TAM were carried out by members of early polar

The Transantarctic Mountains.

exploring expeditions. Members of the British National Antarctic Expedition were the first to find their way through the TAM and onto the Polar Plateau. Then historically significant overland traverses were made into Victoria Land and onto the Polar Plateau by Ernest Shackleton's British Antarctic *(Nimrod)* Expedition and Douglas Mawson's Australasian Antarctic Expedition, which helped determine the position of the South Geomagnetic Pole. On their fateful return from the South Pole in early 1912, Scott's polar party collected rock specimens along Beardmore Glacier, as had Shackleton's 3 years before.

Geologists accompanying US and Australian expeditions in the 1920s and 1930s did periodic reconnaissance. Comprehensive surveying, geological mapping, and study of rock exposures began in earnest with activities of the International Geophysical Year, begun in 1957. Active geological research in the TAM today is sponsored primarily by the national programs of Germany, Italy, New Zealand, the United Kingdom, and the United States.

No mineral deposits of economic value are known in the TAM. Large volumes of early Paleozoic and Jurassic igneous rocks underlie the mountain belt, including granites of continental-margin volcanic-arc affinity and gabbros found in mafic layered intrusions. Similar occurrences of igneous rocks host important economic mineral deposits in other parts of the world (for example, copper and platinum-group elements), but no indications of such mineralization are known here. Thin coal seams in Gondwana strata of the Beacon Supergroup are of low rank, making them of greater interest for paleoclimate reconstructions than as a potential economic mineral resource.

The TAM sit astride the western limit of Precambrian crustal rocks representing the East Antarctic craton. This is one of Earth's oldest continental assemblies, dating to nearly 4 billion years ago, and shows evidence of tectonic reactivation during mountain-building events about 1 billion and 600–500 Ma. Nearly the entire shield is covered by the modern East Antarctic ice sheet, so knowledge about its age and composition comes primarily from scattered coastal exposures. Presence of Precambrian basement underlying the TAM comes from rare exposures within the mountain belt and geophysical imaging of rocks beneath the adjacent polar ice cap.

Exposures of Archean and Proterozoic basement in the TAM are restricted to the Nimrod Group, mapped in the central region of the mountain belt. Despite the effects of younger metamorphism and deformation during the Ross Orogeny, these high-grade metamorphic and igneous rocks record a rich Precambrian geologic history of the East Antarctic craton that spans 2.5 billion years of Archean to early Paleozoic time. Recognized events include primary Archean magmatism from 3150–3000 Ma, crustal stabilization and metamorphism from 2955–2900 Ma, partial melting at about 2500 Ma, deep-crustal metamorphism and magmatism from 1730–1700 Ma (Nimrod Orogeny), and basement reactivation involving high-grade metamorphism, magmatism, and penetrative deformation during the Ross Orogeny from 540–515 Ma.

The presence of Precambrian cratonic basement along the eastern side of the TAM, where such rocks are not exposed, is revealed by geophysical methods that image through the ice cover. Gravity and magnetic data, for example, show that thick continental lithosphere beneath the ice cap traces the western limit of the modern TAM. East Antarctic lithosphere is thought to be a key part of the late Precambrian supercontinent of Rodinia, which formed by collision and amalgamation of several large continental cratons about 1 billion years ago (Grenville Orogeny). Beneath and to the west of the TAM, Antarctic lithosphere is thinner and younger. The coincidence of this change in lithospheric character with the TAM suggests that the modern mountain belt overlies an ancient continental rift margin. Geological, stratigraphic, and geochronological data from rare outcrops indicate that rifting occurred from about 750–680 Ma, separating what became East Antarctica to the east from a conjugate continental plate to the west. Some workers interpret paleogeographic and paleomagnetic data to indicate that East Antarctica rifted from present-day North America, but this interpretation is controversial. Although the identity of the conjugate margin to East Antarctica is debated, the geometry and nature of the late Precambrian rift margin in Antarctica shaped subsequent geologic events in the TAM. Between the time of rift separation and convergence associated with the Ross Orogeny, the paleo-Pacific continental margin of Antarctica was blanketed by late-Neoproterozoic clastic sediment, interlayered with minor volcanic material, culminating in deposition of thick Lower Cambrian reef carbonates deposited on a mature continental platform during a period of global sea-level rise. Marine fauna in the carbonates suggest that East Antarctica resided in a low-latitude position and was geographically linked with other extant continents.

The western rift margin of East Antarctica coincided with the breakup of Rodinia, but formation of the Gondwana supercontinent transformed the TAM margin of Antarctica to an active convergent boundary. Subduction along this margin of Antarctica occurred in response to closure of the ancient Mozambique Ocean and collision within the East African Orogen beginning about 600–500 Ma (also known generally as the Pan-African Orogeny). The resulting Ross Orogeny in Antarctica refers to the period of latest Proterozoic and early Paleozoic tectonic activity related to continental-margin subduction like that occurring in the modern Andes Mountains. Initial deformation linked to Ross activity is preserved in deep-seated crystalline basement as well as in the older rift-margin deposits and can be traced to about 540 Ma. Some orogenic sedimentary deposits contain igneous detritus of similar age, suggesting erosion of a huge continental-margin batholith belt that is a central signature of Ross activity. The breadth and character of deformation, metamorphism, magmatism, and orogenic sedimentation suggest that the Ross Orogen was similar in scale to other large mountain belts, and it is well-exposed today as basement to the modern TAM. Orogenic features related to Ross shortening and magmatism can be traced from the Ellsworth and Pensacola Mountains to the Queen Maud and Queen Elizabeth mountains, then northward along the main spine of the TAM to Victoria Land; correlative tectonic features are found in the Delamerian Orogen in Australia.

The principal characteristics of the Ross Orogen are regional contractional deformation, emplacement of widespread granitoid magmas, and variable metamorphism of both high-temperature and high-pressure types. In detail, deformation was partitioned into both orogen-normal and orogen-parallel displacements, suggesting that convergence was oblique. The vast scale of magmatism forming the Ross batholith belt, including early alkaline compositions and main-phase calc-alkaline rocks, is most certainly a product of convergent-margin magmatism. As such, the calc-alkaline Ross-age igneous rocks represent significant primary magmatic additions to the Antarctic lithosphere. Evidence for eastward subduction of paleo-Pacific oceanic lithosphere beneath cratonic East Antarctica comes primarily from geochemical and isotopic variations in granitoid magmas, which show an eastward increase in continental signature. Ross-age igneous rocks span at least 80 million years during the orogenic cycle and include intrusions that predate deformation, are synchronous with it, or cut across deformation features. They intrude older metamorphic roots of the orogen, as well as young orogenic deposits. Ross metamorphism is highly variable in character, and includes high-temperature magmatic-arc metamorphism, high-pressure metamorphism due to crustal thickening and oceanic-arc collision, and low-grade metamorphism associated with seaward growth by plate-margin accretion. Regional metamorphism in pre-Ross sedimentary assemblages is typically of medium grade, but high-temperature rocks and migmatites that formed by local partial melting occur in the Miller Range (Nimrod Group) and Mountaineer Range (Wilson Group); eclogites, rocks formed at very high pressures, in northern Victoria Land attest to profound crustal thickening during Ross convergence. Thick accumulation of orogenic clastic sediments (mainly deposited in forearc basins in northern Victoria Land, the central TAM, and the Pensacola Mountains) reflect significant erosion within the mountain belt, consistent with thermochronologic evidence of rapid late-orogenic denudation.

Ross Orogen tectonic activity diminished through the Ordovician period (in most areas by about 480 Ma) and this region of Antarctica became tectonically quiet by the Early Devonian. Prolonged denudation reduced the Ross mountain belt to a continent-wide flat erosional surface, called the Kukri peneplain. This surface is well exposed in many places as an unconformity boundary separating basement rocks below from sedimentary and volcanic successions of the Beacon Supergroup above. It is an easily identifiable marker used to determine the magnitude of younger differential uplift. Some 2.5–3.0 kilometers of terrestrial sediment, mostly clastic sequences of quartz-rich fluvial conglomerate, sandstone, and mudstone, were deposited between Devonian and Triassic time (over 150 million years). This well-known upper Paleozoic and lower Mesozoic Gondwana sequence includes Devonian to Carboniferous shallow-marine and nonmarine clastics; Upper Carboniferous to Lower Permian glacial and glacial-marine rocks; Lower Permian marine, deltaic, fluvial, and lacustrine rocks; Upper Permian fluvial, lacustrine, and deltaic coal measures; and a thick succession of Triassic fluvial rocks. Correlative successions extend from South America to Australia, Africa, and India, suggesting a broad network of terrestrial basins.

Beacon strata contain rich plant, invertebrate, vertebrate, and trace fossil assemblages critical for paleogeographic and paleoenvironmental reconstructions marking the end of major glaciations on the Pangea supercontinent. These include Permian and early Triassic fluvial and lacustrine deposits containing extensive *Glossopteris* leaf-litter beds, petrified forests, and fossil crayfish and burrows, indicating a near-polar terrestrial environment. By Triassic time, Antarctica had drifted northward to lower paleolatitudes along with its African and Australian craton neighbors. Deposits of this age contain tetrapod fossils of *Lystrosaurus*- and *Cynognathus*-type reptiles and amphibians, and anatomically well-preserved fossil plants and pollens, some as silicified remnants in petrified forests. Antarctica reached its most northerly paleolatitude position at the end of Pangea time, and the uppermost Beacon deposits of the TAM contain recently discovered Jurassic vertebrates, both dinosaur and pterosaur faunas, suggesting a moderate-climate terrestrial ecosystem. Thus, the Gondwana sequence of the TAM records a progressive terrestrial climate shift from glacial conditions to subpolar, wet–temperate, and arid conditions.

Much of the present physiographic expression of the TAM can be traced to its Mesozoic history during early fragmentation of the Gondwana supercontinent, which resulted in continental rifting and separation of the Antarctic lithosphere from parts of present-day South America and Africa. In the TAM, the large-scale plate movements led to widespread Jurassic igneous activity and extensional deformation generally perpendicular to the modern trend of the mountain belt. Magmas collectively referred to the Ferrar Magmatic Province erupted as basaltic flows onto both wet and dry Beacon landscape surfaces and they were emplaced as individual subsurface intrusions. One of the most prominent of these, the Dufek intrusion, is similar to other mafic-layered intrusions worldwide except for a lack of known economic mineral occurrences. In many areas, Ferrar magmas were injected within Beacon strata as a swarm of laterally extensive sheet-like sills, enhanced in cliff exposures by glacial erosion. Geochronology shows that the Ferrar sills were emplaced over a geologically brief period about 175–180 Ma, yet they can be traced the entire length of the TAM. Individual sheets may be hundreds of meters thick and can be traced for tens and hundreds of kilometers. The Ferrar Magmatic Province extends over 3000 km along nearly the full length of the TAM and is contemporaneous with similar rocks in Australia, South America, and southern Africa. Ferrar magmas are thought to result from high-temperature melting of a mantle source, overlying mantle plumes or associated with back-arc spreading.

Jurassic magmatism was accompanied by crustal extension, which displaced some basement rocks westward toward Marie Byrd Land and contributed to differential uplift within the present-day intraplate mountain belt. Mesozoic extension is expressed mainly by distributed, relatively small-offset fault arrays, and did not result in complete rifting of Antarctica along its paleo-Pacific margin. The amount and timing of Mesozoic extension is poorly known, but appears to be of similar magnitude to the Basin and Range province of North America.

Extension continued episodically from Cretaceous into Cenozoic time, leading to crustal thinning and widening of the Ross Sea basin and movement along steep, orogen-parallel normal faults within the TAM.

With few exceptions, major range-front faults are covered by the Ross Ice Shelf at the base of the mountains, but they are inferred to mark the sharp geomorphic break. Mapped faults define an asymmetric pattern formed mainly by down-to-the-west normal faults. Displacement on individual structures defining this rift-shoulder extensional system is up to several hundred meters, with cumulative vertical displacement of 5 km. Uplift attributed to this displacement started by about 120 Ma, but a major period of extension beginning about 55 Ma produced as much as 4 km of denudation over just the past 30 million years (since Oligocene time). Cenozoic volcanism in the eastern Ross Sea region is thought to be an expression of this extensional setting. Contrasting geologic units along the edges of modern large outlet glaciers suggests that extension was accommodated by transverse structures reactivated along earlier rift-phase and Ross-orogen features. Geodetic data indicate that neotectonic uplift continues and active alkaline volcanism in the McMurdo area is attributed to residual intraplate extension between East and West Antarctica.

Cenozoic volcanism along the western and southwestern Ross Sea margin of the TAM is marked by Oligocene and younger alkali basalt centers, the largest of which is Mount Erebus. Volcanism of the McMurdo Volcanic Group began about 25 Ma, but many of the volcanoes in the region are Pliocene to recent age and now dormant. Mount Erebus (about 3800 m) on Ross Island is the world's southernmost historically active volcano. Its summit contains an active lava lake, contained within a composite caldera structure. Volcanic activity has been continuous since 1972, producing strombolian eruption of cinders and volcanic bombs on the crater rim.

The modern TAM form a nearly continuous ice barrier between East and West Antarctica. Ice flows generally away from the mountain belt, except where high-standing ice of the East Antarctic ice sheet drains through individual outlet glaciers into the Ross Sea. Katabatic-type polar winds ablate relatively stagnant ice dammed against the mountain buttress, leaving behind a lag of rocky debris, including numerous meteorites. Modern and recent climate patterns are controlled in part by the balance of ice present in the major ice sheets to either side of the mountain belt. Although the modern alpine features of the TAM reflect ongoing glacial erosion, some parts of the belt, particularly in the Dry Valleys of Victoria Land, contain glacial deposits and landscape surfaces that suggest polar desert conditions extending back at least 17 million years. Present research is directed to the question of whether the East Antarctic ice sheet has existed continuously at the edge of the TAM since Miocene time, or whether glaciation was episodic.

John W. Goodge

See also **Australasian Antarctic Expedition (1911–1914); Beacon Supergroup; Borchgrevink, Carsten E.; British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); British Antarctic *(Nimrod)* Expedition (1907–1909); British Antarctic *(Southern Cross)* Expedition (1898–1900); British Antarctic *(Terra Nova)* Expedition (1910–1913); British Antarctic *(Terra Nova)* Expedition, Northern Party; British National Antarctic *(Discovery)* Expedition (1901–1904); Coal, Oil, and Gas; Dry Valleys; East Antarctic Shield; Ferrar Supergroup; Fossils, Invertebrate; Fossils, Plant; Fossils, Vertebrate; Geological Evolution and Structure of Antarctica; Gondwana; International Geophysical Year; McMurdo Volcanic Group; Meteorites; Rodinia; Plate Tectonics; Victoria Land, Geology of; West Antarctic Rift System**

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UKRAINE: ANTARCTIC PROGRAM

The State Program of Ukrainian Research in Antarctica for 2002–2010 is the integrated program that defines the strategy of Ukrainian activity in Antarctica. The main tasks of the program are fundamental and applied scientific Antarctic research in the field of global climate change, space weather, and ecosystem monitoring. The program's budget for science and infrastructure since 2000 equals US$1.3 million.

The Ukrainian Antarctic Center (UAC) provides research in Antarctica within the Ukraine Ministry of Education and Science as national operator. The UAC staff consists of fifty people. The scientific division includes the groups of scientific support, informational support, and the Antarctic Treaty supervising, publicity, and publishing section. The logistics division involves the groups of logistical procurement, technical services, communications, and personnel training. The network of UAC includes five scientific laboratories in conjunction with institutes of the National Academy of Sciences and universities

The Ukraine acceded to the Antarctic Treaty on September 1992, and in 1994 became a member of CCAMLR and an associate member of SCAR. In 2001 Ukraine adhered to the Protocol on Environmental Protection to the Antarctic Treaty. In May 2004 Ukraine became the twenty-eighth Consultative Party in the Antarctic Treaty System.

On 6 February 1996 the British Antarctic base Faraday was transferred to Ukraine and renamed Vernadsky station (65°15′ S, 64°16′ W). This event started Ukrainian Antarctic research as an independent state. At Vernadsky station, Ukrainian scientists carry out research in upper-atmosphere physics and geomagnetic field, total ozone observations, tide measurements, meteorology and climate, biology, glaciology, human biology and medicine, and ecology. The surface meteorology and hydrology observations, total ozone and tide measurements, ionosphere soundings, geomagnetic field registration, UV-B observation, electromagnetic signals observations in VLF, ELF, and HF bands (whistlers, Schumann and Alfven resonances, geomagnetic micropulsations, traveling ionosphere disturbances), and seismic–acoustic measurements are carried on year round to study the energy transfer processes from the Earth's surface to geospace. The geomagnetic data from Vernadsky have been sent to the INTERMAGNET network. The total ozone measurements are provided to study the ozone hole and atmospheric planetary wave dynamics. Mass-balance and glacier displacement in the Antarctic Peninsula region is the glaciology topic. In biology the research and monitoring of marine mammal and bird population conditions and the genetic structure of the krill population is carried out. The geophysical monitoring of West Antarctica to study deep processes in the lithosphere, its influence on the environment, and construction of the evolution of the geodynamic model of region is studied. In ecology the waste management and radioactive contamination-reducing processes in the human organism during winter are studied.

In logistics, R/V *Ernst Krenkel* was used for Vernadsky supply operation and scientific activity in 1997–1999, and R/V *Gorizont* sailed as the supply ship in 2000–2002. The Vernadsky supply scheme—air flight to Ushuaia and a ship charter across the Drake Passage—has been used since 2002. In 1997–2002 the UAC Bulletin was edited as a scientific journal in which the Ukrainian Antarctic research results are published. In 2003 the Bulletin was transferred to the multidisciplinary Ukrainian Antarctic Journal.

GENNADY MILINEVSKY

See also **Antarctic Treaty System; British Antarctic Survey; Conservation of Antarctic Fauna and Flora: Agreed Measures; Protocol on Environmental Protection to the Antarctic Treaty; Scientific Committee on Antarctic Research (SCAR)**

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ULF PULSATIONS

During magnetic storms the geomagnetic field is greatly disturbed, and consequently at polar latitudes a compass needle can wander on a time scale of seconds to an hour or longer, for example during auroral substorms. Intense work during the International Geophysical Year in 1957–1958 established that small, periodic oscillations of the geomagnetic field occur virtually at all times and across the globe. These variations are called geomagnetic pulsations, and their occurrence and amplitude peak at high latitudes. In records from magnetometers, the pulsations are generally of two types. Regular, sinusoidal oscillations with periods between about 0.1 and 1000 sec are called continuous pulsations (Pc), and usually occur during local daytime. They last for minutes to hours and have amplitude typically around 1 nanoTesla (nT) for 30-sec pulsations, but they are much smaller at shorter periods (for comparison, the main background geomagnetic field has an intensity of 50,000–60,000 nT). At local night the pulsations usually have a more irregular, transient appearance (called Pi) and are associated with auroras and radio noise.

Geomagnetic pulsations have been extensively studied using arrays of high-precision magnetometers, using radars that reflect high-frequency radio signals from auroral features, and using magnetic and electric field measurements from spacecraft. It is now known that geomagnetic pulsations are the signature of ultra-low-frequency (ULF—frequency in the range of 1 mHz–10 Hz) waves that propagate through the magnetosphere of the Earth. These ULF waves result from the interaction of the solar wind with the geomagnetic field. The existence of such waves was first predicted in the theory of magnetohydrodynamics (MHD), developed by Hannes Alfvén, who was awarded the 1970 Nobel prize for this work. MHD describes electrically conducting gases in a magnetic field, such as the environment of the solar wind and the magnetosphere. These hydromagnetic waves propagate at what is called the Alfvén speed, which in the magnetosphere is around 1000–2000 km/sec. Thus ULF waves may travel through the entire magnetosphere to the earth in around 1 min.

There is strong evidence that ULF waves enter the magnetosphere from the upstream solar wind and are also generated at the magnetopause boundary when it undergoes rapid deformation under the action of the solar wind. The waves typically have dimensions comparable to the size of the entire magnetosphere, and may therefore establish oscillations along the geomagnetic field lines that map from the earth's surface into space like field lines from a bar magnet. Some waves are also generated locally within the magnetosphere, by gaining energy from charged particles orbiting the earth in the radiation belts. Finally, irregular ULF waves are associated with the transient magnetic fields generated by precipitating energetic particles responsible for auroras.

ULF waves carry energy from the solar wind throughout the magnetosphere but can also be used to monitor processes in space. This includes space weather effects that can, for example, degrade the performance of radio communications, surveillance radars, and satellites. Space telescope images show that auroras occur on Jupiter and Saturn, and spacecraft have recorded ULF waves in the magnetospheres of those planets.

FREDERICK MENK

See also **Aurora; Auroral Substorm; Geomagnetic Field; Geospace, Observing from Antarctica; International Geophysical Year; Magnetic Storm; Magnetosphere of Earth; Plasmasphere; Solar Wind**

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UNITED KINGDOM: ANTARCTIC PROGRAM

Britain has a rich history of involvement in Antarctic affairs, which has shaped and set the context for how the programme is currently structured. The Scott Polar Research Institute (SPRI) was established, by public subscription, in 1920 within Cambridge University as a memorial to Captain Robert Falcon Scott and his four companions, who perished on their way back from the South Pole in 1912. It is now part of the Department of Geography of the University. The British Antarctic Survey (BAS), also located in Cambridge, developed from a secret military operation during World War II and is now a wholly owned component body of the UK Natural Environment Research Council (NERC). The Polar Regions Unit (PRU) of the UK Foreign and Commonwealth Office (FCO) has its roots in the British claim to Antarctic territory (the Falkland Islands Dependencies [FID]) lodged by Letters Patent in 1908, and more directly from the appointment of Dr. Brian Roberts (ex-British Graham Land Expedition) by the FCO in 1944 to deal with polar political problems and plan policy for the FID. The unit has been in existence in one form or another continuously since then. The Royal Navy has also had a long association with Antarctic affairs, extending back to the early explorations of James Cook and James Clark Ross, but in more modern times (since the Second World War) through the provision of an "Ice Patrol Vessel," currently HMS *Endurance,* which deploys annually to the South Atlantic.

The PRU is responsible for UK policymaking and representation in Antarctic matters in the international political arena. The PRU takes the lead at meetings of the Antarctic Treaty System (ATS), at the Council for Conservation of Antarctic Marine Living Resources (CCAMLR), and at the other subsidiary conventions of the ATS. It also represents UK interests at political fora concerned with Arctic affairs.

BAS provides the physical UK presence in Antarctica on behalf of the UK government. BAS has a dual mission: to undertake a world-class programme of science, and to sustain for the UK an active and influential presence and a leadership role in Antarctic affairs. BAS is funded from money provided by the British government for basic science that is channelled through the UK Research Councils. Since the funding is via this route the BAS science programme is not directly determined by government, and nowadays is set through a process of stakeholder and public consultation in the context of the broad strategic research aims of NERC, and subject to rigorous international peer review. The core programme is planned and resourced on a 5-year cycle between reviews. The BAS philosophy is to conduct research on global questions of concern to humankind using the opportunities offered to study the Earth system in the Antarctic setting. BAS also puts emphasis on maintaining key long-term observations of the environment and in continuing a programme of survey. It is enthusiastic about collaboration and maintains a strong programme of public engagement and outreach.

Although BAS is within a research council, its dual mission has meant that it is not possible for its strategy to be decoupled from the primary interests of government. Thus the long-term strategic planning for BAS is dealt with by an interdepartmental group that has representation from the FCO, Treasury, the Office of Science & Technology (of the Department of Trade & Industry), NERC, and BAS.

BAS is an integrated operation providing both the logistics and the scientific effort from within its own staff and resources, which makes it distinctly different from most other national operators. BAS operates two major year-round research facilities in Antarctica, at Rothera Point on Adelaide Island (Rothera Station) and on the Brunt Ice Shelf in the southern Weddell Sea (Halley Station). In addition, two smaller year-round research stations are maintained on the sub-Antarctic Island of South Georgia (at King Edward Point and on Bird Island), and a summer-only station is operated on Signy Island (South Orkney Islands). The BAS has two ice-capable vessels: the Royal Research Ships *Ernest Shackleton* and *James Clark Ross*. The former is primarily for logistical support whilst the latter provides a very sophisticated ocean research platform. BAS operates a fleet of four DHC-6 ski-wheel Twin Otter aircraft within the Antarctic and one DHC-7 (wheels only) aircraft whose primary role is to provide an intercontinental link between the Falkland Islands and Rothera Station. BAS provides expert advice to PRU for ATS and CCAMLR matters and is responsible for representation at the Council of Managers of National Antarctic Programmes (COMNAP). For 2005, the overall budget of BAS was circa £40M and the staff was circa 475 people.

The Royal Navy vessel HMS *Endurance* provides direct logistical support to BAS operations, primarily through the provision of her two helicopters. She is also engaged in a long-term programme of hydrographic survey around the Antarctic Peninsula, adjacent islands, and South Georgia.

Although most of the funding for research is channelled through BAS, the NERC also operates a responsive mode competitive scheme, known as the "Antarctic Funding Initiative," which provides funds for UK academics (and BAS staff) for Antarctic research using the BAS logistical capability.

SPRI does not have an in-house logistical capability, but has a broad portfolio of research in both the Antarctic and Arctic, and carries out postgraduate teaching in polar matters. It is also the home of one of the finest polar libraries in the world (the Shackleton Memorial Library), the Thomas H. Manning Polar Archives, and a comprehensive collection of polar maps. The secretariat for the Scientific Committee for Antarctic Research (SCAR) is based at SPRI, as are the World Data Centre for Glaciology and the International Glaciological Society. In addition, there is a museum of polar artefacts that is open to the public. There are also several other significant university groups in the UK carrying out research in, on, or related to Antarctica.

The Royal Society is the British national academy for science. It has taken an interest in Antarctic research since it sponsored the expedition that established the first Halley station in 1956 as part of the UK contribution to the International Geophysical Year. This interest continues through the its National Committee for Antarctic Research, the forum for coordinating the UK involvement in SCAR comprising leading scientists from BAS, SPRI, and the broader UK academic community.

JOHN R. DUDENEY

See also **Antarctic Peninsula; Antarctic Treaty System; British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); British Antarctic *(Terra Nova)* Expedition (1910–1913); British Antarctic Survey; British Graham Land Expedition (1934–1937); Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Council of Managers of National Antarctic Programs (COMNAP); Cook, James; Earth System, Antarctica as Part of; International Geophysical Year; Scientific Committee on Antarctic Research (SCAR); Scott Polar Research Institute; Scott, Robert Falcon; South Georgia; South Orkney Islands**

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UNITED NATIONS

In 2005, the sixtieth anniversary of the United Nations (UN) marked the organisation's enduring, frequently significant role in international affairs. For many, the UN represents the obvious mechanism for resolving, or at least managing, international problems. Unsurprisingly, Antarctica, a region characterised by uncertain, indeed disputed, ownership and a perceived conflict potential, has often been presented as a prime case for UN treatment, especially given concerns about economic exploitation and conservation alongside a growing awareness of the continent's integral role in global environmental systems. However, in practice, the UN has proven to be, and remains still, only a marginal player in Antarctic affairs. Instead, individual governments, acting both individually (e.g., through national scientific research programmes) and collectively through the Antarctic Treaty System (ATS), have performed the principal roles.

Despite occasional calls after 1945 for UN intervention, the governments active in Antarctica preferred a more direct approach, culminating in the 1959 Antarctic Treaty. Thenceforth, the region has been managed by the Antarctic Treaty parties (ATPs), working through the ATS. Nevertheless, in 1983, the Malaysian government and its supporters, guided by environmental NGOs, placed the "Question of Antarctica" formally on the UN's agenda. They argued the case for treating Antarctica, like the deep seabed, as the common heritage of humankind managed by a UN-based body in place of what was presented as the unaccountable, undemocratic, and nontransparent ATS. The participation of the apartheid South African government in the ATS was a further target for attack. By contrast, the ATPs asserted that Antarctica was managed by a valid, successful, and comprehensive regime open to accession by any UN member.

Sharp divisions between ATPs and their critics meant that the UN's initial consensus approach soon broke down in 1985. Restored in 1994, a consensus approach prevails still today. ATPs and non-ATPs, albeit still agreeing to differ about how to manage Antarctica, accept the need to work for change within the ATS framework. The UN remains seized of the "Question of Antarctica," but the critical campaign has lost much of its momentum. Thus, the topic is now placed on the UN agenda upon only a triennial basis—the last reference was in late 2005—and there is even growing speculation about Malaysian accession to the Antarctic Treaty.

Although the UN's post-1983 involvement in Antarctica has often been dismissed as somewhat ritualistic, the episode has encouraged a more informed appreciation upon the part of the broader international community of the nature and significance of Antarctica, the ATS, and polar science. Indeed, the UN Secretary-General's reports, produced to guide each UN session on Antarctica, offer a useful up-to-date reference source. At the same time, the UN-based challenge, though treated by ATPs as a low priority, has fostered a greater sense of purpose and unity between them alongside an awareness of the need to do more by way of selling the ATS's merits to a wider audience and the prudence of involving the UN's specialised agencies, like the United Nations Environment Programme (UNEP), in its work.

PETER J. BECK

See also **Antarctic Treaty System; Antarctic and Southern Ocean Coalition (ASOC); Geopolitics of the Antarctic; Greenpeace; United Nations Convention on the Law of the Sea (UNCLOS); United Nations Environmental Programme (UNEP)**

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UNITED NATIONS CONVENTION ON THE LAW OF THE SEA (UNCLOS)

The United Nations Convention on the Law of the Sea was negotiated at the Third UN Conference on the Law of the Sea (UNCLOS III), held from 1973 to 1982. The convention was opened for signature at Montego Bay, Jamaica on 10 December 1982. On that day it attracted 119 signatures, yet it took 12 years—until 16 November 1994—for the convention to enter into force. In following years the convention secured an almost universal participation: to date (1 June 2006) there are 149 parties to the convention. This was facilitated by the adoption, on 28 July 1994, of the agreement relating to the implementation of Part XI of the Convention, on the international seabed area.

That aspect of the convention is related to the origin of the initiative for UNCLOS III and can be traced back to the 1967 UN General Assembly discussion of the concept of the common heritage of humankind and the seabed beyond the limits of national jurisdiction. However, when UNCLOS III eventually began in 1973, it started from a far broader platform: consciousness that the problems of ocean space are closely related and need to be considered as a whole.

The result was the convention, consisting of 320 articles and 9 annexes, containing both codification of customary norms and progressive development of international law. Included are rules on various maritime zones and areas: territorial sea, contiguous zone, straits used for international navigation, archipelagic waters, exclusive economic zone, continental shelf, high seas, and the international seabed area. The convention also devotes special parts to enclosed/semi-enclosed seas and the rights of land-locked states. Protection of the marine environment, scientific research, technology transfer, and settlement of disputes are all addressed. New institutions were established under the convention: the International Seabed Authority, the International Tribunal for the Law of the Sea, and the Commission on the Limits of the Continental Shelf. A meeting of states' parties to the convention has been held annually since 1994, while the UN Secretary-General has reported annually since 1984 on key law-of-the-sea developments.

Due to its features the convention is often referred to as the "Charter of the Oceans," a framework treaty that governs all major issues of the entire ocean space.

Part of that ocean space surrounds Antarctica. Here, however, the Antarctic Treaty and its related instruments also apply. Most of the current twenty-eight Antarctic Treaty consultative parties are simultaneously parties to the convention, with the exception of three states: the United States, Peru, and Ecuador. While in defining the limits of maritime zones the convention relies on the notion of a coastal state, the entire Antarctic Treaty System is built around a delicate balance of positions of sovereignty claimants and nonclaimants. There can be no doubt that the convention does apply to Antarctic waters, yet serious questions have been raised regarding various aspects of that application, including the extent of the high seas, the proclamation of coastal zones, the application of Part XI, and, more recently, the continental shelf beyond 200 nautical miles.

DAVOR VIDAS

See also **Antarctic Treaty System; Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Convention on the Regulation of Antarctic Mineral Resource Activities (CRAMRA); Geopolitics of the Antarctic; Protocol on Environmental Protection to the Antarctic Treaty; Southern Ocean; United Nations**

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UNITED NATIONS ENVIRONMENTAL PROGRAMME (UNEP)

UNEP was established in 1972 to provide leadership and encourage partnership in caring for the environment by inspiring, informing, and enabling nations and peoples to improve their quality of life without compromising that of future generations.

UNEP's involvement in Antarctica and the Southern Ocean stems from the critical role they play in the global environmental system. Major processes of interaction between the atmosphere, oceans, ice, and biota affect the entire global system through feedbacks, biogeochemical cycles, circulation patterns, transport of energy and pollutants, and changes in ice mass balance. In addition, the region is of immense value for the conduct of research essential to understanding the global environment.

Through its various programmes, UNEP addresses assessment, management, and policy aspects of global and regional environmental issues, many of which are relevant to Antarctica and the Southern Ocean.

UNEP has closely linked global programmes on the conservation, management, and monitoring of the marine environment and its living resources. These programmes include the Global Plan of Action for the Conservation, Management and Utilization of Marine Mammals; the Global Programme of Action for the Protection of the Marine Environment from Land-Based Activities; and the Regional Seas Programme. Major periodic coordination meetings are organized among the regional seas to share experiences, to which the Convention for the Conservation of Antarctic Marine Living Resources is also invited.

The assessment programme of UNEP has responsibility for keeping under review the state of the environment. UNEP launched the fourth volume of the *Global Environment Outlook* series in 2004, where specific chapters are dedicated to the poles.

UNEP administers the secretariats of various global conventions dealing with subjects directly relevant to Antarctica and the Southern Ocean. They include the Vienna Convention for the Protection of the Ozone Layer and its Montreal Protocol on Substances that Deplete the Ozone Layer; the Stockholm Convention on Persistent Organic Pollutants; the Convention on Biological Diversity; the Convention on International Trade in Endangered Species of Wild Fauna and Flora; and the Convention on the Conservation of Migratory Species of Wild Animals, under which the recent Agreement on the Conservation of Albatrosses and Petrels was negotiated.

UNEP has the responsibility of preparing the report of the United Nations Secretary-General on the Question of Antarctica, which is submitted every 3 years to the General Assembly of the United Nations. To this end, UNEP is invited to attend the Antarctic Treaty Consultative Meetings as an expert organization. UNEP contributes to these meetings by the submission of technical papers that cover a range of issues including the practice of inspections, bioprospecting, and the status of conservation of Antarctic mammals and birds.

UNEP's involvement in polar areas requires policy guidance and coordinated inputs from UNEP substantive units, including UNEP's Key Polar Centre, GRID-Arendal in Norway. To this end, a Polar Task Force has been established that convenes on an *ad hoc* basis to discuss and decide upon policy issues and to a lesser degree on operational matters in the poles.

CHRISTIAN LAMBRECHTS

See also **Albatross and Petrels, Agreement for the Conservation of; Antarctic Treaty System; Convention on International Trade in Endangered Species of Wild Flora and Fauna (CITES); Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Earth System, Antarctica as Part of; United Nations**

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UNITED STATES: ANTARCTIC PROGRAM

The United States Antarctic Program is the principal expression of US interest in Antarctica and the Southern Ocean. Its purpose, as a presidential memorandum states, is to maintain an active and influential national presence responsive to US scientific, economic, and political objectives; the presence is stated to include science in major disciplines and year-round occupation of the South Pole and two coastal stations. A later presidential directive states that fundamental aims in the Antarctic are to protect the environment, preserve research opportunities, maintain the peace, and conserve marine living resources. The US Congress authorizes public funding for the program in response to annual requests made by the President.

The program helps the United States fulfill obligations under the Antarctic Treaty, to which the nation is signatory. Other international affiliations include the Council of Managers of National Antarctic Programs and the Scientific Committee on Antarctic Research.

The National Science Foundation (NSF), an agency of the US Government, manages the US Antarctic Program. Using the funds that the Congress has appropriated, it finances nearly all US research and operational support conducted in the Antarctic. Spending in fiscal 2004 was US \$265.56 million. Of this total, \$45.20 million was for research grants, \$152.29 million was for operations and science support, and \$68.07 million was for logistics. These annual levels are typical. The Congress occasionally allocates additional funds to the NSF for special projects such as the rebuilding of Amundsen-Scott South Pole Station.

The NSF is not an Antarctic institute and does not perform research. Scientists employed by universities and other institutions throughout the nation perform these functions, having submitted proposals to the NSF to do so. A major contractor to the NSF provides operational support in the Antarctic, and other contractors provide specialized services such as helicopter operations. The US military provides logistics including intercontinental airlift, sealift, icebreaking, operational weather forecasting, and LC-130 ski airplane operations.

While the United States has no central Antarctic institute, the NSF does fund specialized Antarctic facilities around the nation including an ice core laboratory, a marine geology research facility and core library, the Antarctic meteorite collection, a polar rock repository, and a center for maps, aerial photographs, and place names.

The NSF's web site (www.nsf.gov) provides information about the Antarctic program, and it lists and describes each research award. Regarding accomplishments, an NSF-funded organization compiles an online directory of data sources resulting from the NSF's Antarctic grants. Publication of Antarctic research results is the responsibility of grantees and occurs mainly in the standard refereed scientific literature. The NSF-funded online *Antarctic Bibliography,* which abstracts and indexes all the world's Antarctic research literature, contains grant numbers of listed publications that resulted from NSF support.

Early US Expeditions

US sealers were in the South Shetland Islands as early as 1819. The sealer Nathaniel B. Palmer, who worked in the Antarctic Peninsula area in 1820 and after whom Palmer Land is named, was one of the first to record a sighting of the Antarctic.

The first US scientist to work in the Antarctic was James Eights, who was naturalist aboard the United States Exploring Expedition of 1830, a voyage that the US Congress commissioned. Eights described some of the region's biota and studied the geology of sub-Antarctic islands, where he discovered fossil plants. The six Antarctic papers he published influenced the work of other naturalists, including Charles Darwin.

The United States Exploring Expedition, led by Lt. Charles Wilkes, US Navy, in 1839–1840, mapped 2500 km of the Antarctic coast south of Australia and proved thereby that Antarctica is a continent.

Richard E. Byrd's hugely popular expeditions in 1928–1930 and 1933–1935 investigated West Antarctica from a wintering station on the Ross Ice Shelf and included, in 1929, the first flight to the geographic South Pole. In the late 1930s, the US Government established the US Antarctic Service Expedition, intended to be permanent but stopped in 1941 because of World War II.

The 1946–1947 US Navy Antarctic Developments Project remains the largest Antarctic expedition, with 4700 personnel, 13 ships, and several aircraft; it made 15,000 mapping photographs. The US Navy Second Antarctic Developments Project and the privately financed Ronne Antarctic Research Expedition occurred the next season. These three expeditions yielded the region's first medium-scale maps and influenced placement of research stations for the 1957–1958 International Geophysical Year (IGY).

During planning for the IGY, the United States agreed to establish a research facility at the geographic South Pole. In December 1955 it began setting up Naval Air Facility McMurdo Sound on Ross Island as a seaport and base from which to fly supplies to the Pole. Amundsen-Scott South Pole and McMurdo stations have operated continuously, year round, since then. Five other US Antarctic stations built for the 18-month IGY are no longer used.

In 1959, the nation established its modern United States Antarctic Program.

Research

Much US Antarctic Program research involves phenomena that are global. Stratospheric chemists at McMurdo demonstrated that man-made chlorinated fluorocarbons cause the ozone hole; this evidence helped the world community in 1987 decide to phase out these and related chemicals. Now US year-round stations monitor the ozone hole for, among other things, the anticipated reduction in size as a result of the 1987 decision. Research also provides understanding of the harmful effects on living organisms of the increased ultraviolet radiation that penetrates the Antarctic atmosphere as a result of the ozone hole.

The West Antarctic Ice Sheet, which if melted would raise sea level some 5 m, is known to have disappeared millions of years ago, and portions now are changing rapidly. Scientists are using satellite data, surface sampling, seismic sensing, and other measures to try to predict future behavior of the West Antarctic Ice Sheet.

The annually deposited layers of the thick Antarctic ice sheet contain information about earlier climate change. Russia, the United States, and France collaborated from 1989 to 1998 to retrieve and study ice core from Vostok, the Russian station in East Antarctica. The coring yielded the longest continuous annual climate record extracted from ice—420,000 years.

Fossil discoveries by US scientists contributed to Antarctica's geologic history and its former connections to other continents. They include the terrestrial *Lystrosaurus,* discovered in 1969 (the dominant taxon of a cosmopolitan fauna of low diversity that survived the great extinctions at the end of the Permian); a fossil mammal discovered in 1982 with Argentine scientists (establishing that Antarctica and South America were connected as recently as 40 Ma); and a dinosaur in 1991, proving dinosaurs lived on every continent.

Research on the impact on biota of extreme cold and extended periods of light and dark is a focus. Some cold and dry areas of the Antarctic are studied as analogies to other bodies in the solar system and to the Late Precambrian Snowball Earth.

Maps ranging from single-sheet maps of the entire continent to large-scale maps of selected areas are produced and published by the US Geological Survey. The entire continent—except some featureless areas—has been mapped at a scale of 1:500,000 or larger.

Antarctica provides a platform for looking outward from Earth; astrophysics and astronomy are major emphases of the US Antarctic Program. Observations at South Pole Station through its cold, clean, dry atmosphere provide viewing in some wavelengths equal in quality to those made from space. Telescopes measure radiation emitted when the universe was young, before stars and galaxies began to form, providing clues about how the universe evolved into its present state.

An instrument array beneath Amundsen-Scott Station uses the homogeneous, clear ice sheet (2900 m deep) as the medium for detecting neutrinos from deep space. Neutrinos carry information very different from that obtained via light telescopes and radio telescopes, and observing them opens a new window to help detect and explain the universe's so-far-undetected forms of mass and energy.

Facilities and Operations

By 1965, the program had its present suite of three year-round stations: two on the coast (McMurdo, as mentioned, and Palmer, on Anvers Island off the west coast of the Antarctic Peninsula), and the interior station on the ice plateau at the South Pole.

In summer (October–February), the approximate population of the US Antarctic Program on the continent (not including ships) rises from winter's few hundred (349 in 2005) to about 1800. The approximate number of science projects rises from 10 in winter to over 125 in summer. About 2500 people a year participate.

Air transport generally takes place only in summer, but it is extensive then, enabling rapid deployment of scientists and support personnel to and from the Antarctic via McMurdo Station, providing almost the totality of transport to and from the South Pole, and making possible the establishment each summer of research camps.

Field camps away from the year-round stations are a major part of the US Antarctic Program, numbering in the dozens over summer, with their populations nearing 200. Camps are located as science requires throughout the Antarctic and vary in size from a tent to an installed facility with heated structures and even running water. The camps usually focus on geology and geophysics, glaciology, and biology. In a typical summer, aircraft flights to support these camps number in the hundreds.

Although airplanes bring to Antarctica the scientists, some research equipment, and fresh food, ships deliver most of the cargo and all of the fuel. McMurdo receives one tanker and one cargo ship, both ice-strengthened but requiring icebreaker escort, each year.

Palmer Station on Anvers Island by the Antarctic Peninsula is serviced entirely by ship (from southern South America) without icebreaker escort. Its location slightly north of the Antarctic Circle makes it accessible by ice-capable ship at any month of the year; the population varies from forty-five in summer to as low as ten in winter. The research emphasis is marine biology.

Year-round automated data collection takes place at remote sites throughout Antarctica. In 2002, a typical year, fifty-two weather stations and six geophysical observatories operated unattended except for brief visits for maintenance.

Southern Ocean research in marine geology and geophysics, marine biology, and oceanography has been extensive since the research ship USNS *Eltanin* (length 81.1 m) surveyed the region between 1962 and 1972, covering 410,000 nautical miles in an Antarctic circumnavigation of 55 cruises.

The program's present-day deep-water research ship is the purpose-built icebreaker *Nathaniel B. Palmer* (93.9 m), which entered service in 1992. This ship supports research in all parts of the Southern Ocean, with a focus on ice-infested areas.

R/V *Laurence M. Gould* (70.2 m), ice capable, transports personnel and cargo to and from Palmer

Station and supports oceanic research mainly along the western side of the Antarctic Peninsula and in the Drake Passage.

Ships of the US academic fleet also have worked in the Southern Ocean on particular research questions. The international Ocean Drilling Program *(Joides Resolution)* and its predecessor Deep Sea Drilling Project *(Glomar Challenger)* have taken deep-sea sedimentary cores south of 60° S, providing information regarding past climates obtainable in no other way. Findings include the 1988 discovery that a much larger Antarctic ice sheet existed 35 Ma.

Icebreakers in the US military fleet have participated in US Antarctic work since the beginning of the IGY, when *Glacier* (94.4 m) helped to establish McMurdo Station. While their primary role is to break channels in sea ice and to escort supply ships, the icebreakers also support research directly.

International Cooperation

International cooperation in research and research support occurs extensively in the US Antarctic Program. At its most straightforward, a US scientist joins a non-US research team or vice versa. Russia and the United States exchanged wintering scientists throughout much of the Cold War.

Other examples of international cooperation include joint research at a US Antarctic facility and entire projects planned from the beginning to be international, such as the Cape Roberts Project (seven nations, led by New Zealand), established to investigate and better understand climatic and tectonic history.

Shared use of facilities and operations has included jointly planned aircraft missions to McMurdo with New Zealand, Italy, and others. The intention always is that, over time, the participating nations contribute effort and derive benefit in commensurate measure.

Guy G. Guthridge

See also **Amundsen-Scott Station; Antarctic Peninsula; Antarctic Treaty System; Aviation, History of; Byrd, Richard E.; Council of Managers of National Antarctic Programs (COMNAP); International Geophysical Year; McMurdo Station; Office of Polar Programs, National Science Foundation, USA; Palmer, Nathaniel; Ronne Antarctic Research Expedition (1947–1948); Ross Ice Shelf; Scientific Committee on Antarctic Research (SCAR); Sealing, History of; United States Antarctic Service Expedition (1939–1941); United States (Byrd) Antarctic Expedition (1928–1930); United States (Byrd) Antarctic Expedition (1933–1935); United States Exploring Expedition (1838–1842); United States Navy Developments Projects (1946–1948); Wilkes, Charles**

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UNITED STATES ANTARCTIC SERVICE EXPEDITION (1939–1941)

Early in 1939, with war threatening around the world, President Franklin D. Roosevelt decided that the United States must, at least temporarily, abandon its historic practice of neither making nor recognizing territorial claims in the Antarctic. Roosevelt was doubtless galvanized by the presence in the far south that austral summer of a German expedition that explored by air somewhere between 135,000 and 230,000 m^2 (350,000 and 600,000 km^2) of the Antarctic continent directly south of Africa. While the German effort seems to have been little more than an attempt to validate existing whaling rights (some whale products were vital in Germany), Roosevelt clearly believed that a German presence near the Antarctic Peninsula posed a threat to the solidarity and defense of the Western Hemisphere should a second world war occur.

At the same time, famed US polar explorer Admiral Richard Byrd was contemplating a third expedition south, as were several of his colleagues from former ventures. Indeed, Finn Ronne was on the verge of purchasing a ship, and Richard Black, working within the Department of the Interior, had aroused interest there in a US-sponsored expedition even before the president made his decision. Once Roosevelt signaled his intent, the elements of what would formally be designated the United States Antarctic Service Expedition of 1939–1941 (USAS) quickly fell into place. Byrd was first contacted by Department of the Interior and State Department officials in January 1939, and the following month he went to Washington, where he met with Roosevelt to lay preliminary plans. Ronne, Black, Paul Siple, Tom Poulter, and others from Byrd's two earlier private expeditions were swiftly recruited and got to work. Through aerial and ground exploration, Roosevelt wanted to reserve and confirm for possible claim the area stretching from Byrd's earlier Little America bases in the Bay of Whales in the Ross Sea over to the Antarctic Peninsula and adjacent areas eastward along the Weddell Sea. While the President initially suggested a new Little America together with a second base somewhere south of Africa's Cape of Good Hope (adjacent to Germany's newly claimed "Neue Schwabenland"), planners soon determined that fulfilling the basic mission objective would require establishment of an "East Base" somewhere on the peninsula.

Roosevelt's desire to keep the expedition a secret for as long as possible severely hindered both funding and development. When word at last leaked out in May 1939, Congress passed an initial US $10,000 funding bill, supplemented by a further $340,000 in July. This support proved so paltry that it was agreed to make the expedition part public and part private. The initial result was to pressure Byrd into contributing all personal resources to the venture, including the polar ship *Bear*. The Admiral and "his boys" soon ran afoul of public opinion as well. Byrd's popularity had waned during the depression-ridden 1930s. He was increasingly accused of being nothing more than a glory- and publicity-seeking hound who mounted expensive adventures while millions of fellow citizens remained bound in want. Congress's decision to transform the USAS into a mixed enterprise fanned public suspicion that the Admiral was looting both the government *and* the private sector for his own advantage.

When the expedition at last scrambled away aboard two small ships (*Bear* and the modern, 3500-ton, steel-hulled Alaska supply ship *North Star*) in the late autumn of 1939, war had come to Europe and public attention had shifted there. Accustomed to being sent off in a blaze of publicity, Byrd found his departure mentioned only in a brief squib at the bottom of page 38 of *The New York Times*.

Nonetheless, the expedition got off to a fine start. Byrd and his men managed to cram a giant, wheeled "snow cruiser" on board, together with three aircraft: a large, long-range Barkley-Grow seaplane, an equally big Curtis-Wright Condor, and a small Beechcraft "satellite" plane designed to operate from the snow cruiser. A firm program of scientific research was in place as a result of several earlier meetings between the newly formed USAS Executive Committee (including Byrd and chief scientist-designate Alton Wade) and members of the National Research Council of the National Academy of Sciences. And on the eve of Byrd's departure, Roosevelt had given him detailed instructions on objectives, centering around the making of claims, either by flags dropped from aircraft or by cairns on the ground. But, Roosevelt cautioned, neither Byrd nor any member of the expedition was to make any claim public without the express authorization of the Secretary of State.

Employing his traditional route, Byrd took his two ships through the Atlantic and Panama Canal, across the Pacific to Dunedin, New Zealand, and then down to the Bay of Whales, where West Base was established under Paul Siple. Once unloaded, *North Star* went back to Valparaiso, Chile for further supplies and, in March 1940, joined *Bear* off the Antarctic Peninsula, where, after a rough several days of exploration, a suitable site for East Base was found on tiny Stonington Island in Marguerite Bay.

Byrd (and apparently Roosevelt as well) contemplated that the two USAS bases would be occupied on a rotating basis for perhaps 5 or 6 years, despite (or perhaps because of) the fact that the world was at war. Roosevelt directed Byrd himself to return after establishing the bases in order to chair the executive committee overseeing the enterprise. In the event, the men were withdrawn and the bases shut down in March 1941 at the close of the austral summer. By this time, war was looming on the American horizon; fears that the Germans might exploit Antarctica for political or military purposes had proven baseless, and Congress could find many better places to spend money. Despite the widespread activities of the USAS in the "Pacific quadrant" of the Antarctic, the United States chose never to make claims, thus negating a major reason for the expedition.

Nonetheless, the USAS accomplished a great deal of valuable science. Despite the failure of the snow cruiser to perform, Byrd and his men mapped by both air and sea the ice-bound and often foggy, cloudy Antarctic coast between the Ross Sea and the Peninsula, which had defied earlier efforts at discovery. Employing dog sleds and light tractors, five small survey, seismic, and geological reconnaissance teams from Little America supplemented and expanded Byrd's aerial reconnaissance. Moving swiftly eastward across lands claimed by New Zealand, they explored much of the unclaimed Edsel Ford and Rockefeller ranges that lay inland from the coast. At Little America itself, Siple and his men did important research into frostbite and the wind-chill factor while performing valuable mid-winter auroral observations in temperatures that reached –60°F Siple later reported that aerial exploration of the Ross Sea area had resulted "in over a thousand useable aerial photographs."

Following severe weather, East Base commander Richard Black dispatched two field survey parties in the 1940–1941 summer. One was led by Finn Ronne and Carl Eklund and the other by Paul Knowles. These explored the base of the Antarctic Peninsula and the adjacent coast along the Weddell Sea. Although Knowles and his two companions never reached "the corner" where the Antarctic Peninsula turned into the Filchner (now Ronne) Ice Shelf, they reached farther south (71°51′ S) than any exploring party to date from that area. Ronne and Eklund walked 84 days and 1200 miles (1920 km) through some of the most treacherous crevasse fields in Antarctica. In several flights, Black subsequently supplemented, confirmed, and, in the case of the far southeastern Peninsula, somewhat extended his colleagues' ground treks and observations.

In November 1941, the American Philosophical Society devoted its monthly meeting to the scientific results of the USAS. Wade and Siple were the chief speakers, and Wade confirmed that the expedition had been terminated the previous spring due to "existing and impending hostilities." The USAS never formally expired. Meetings of its executive committee chaired by Admiral Byrd continued until allocated funds ran out in May 1942. But, smothered by wartime preoccupations, it was never revived.

As with the first two Byrd expeditions, neither the USAS nor its government or private sponsors published a formal account of its scientific endeavors, although a few papers did appear during the war. Nor are there any books or articles devoted exclusively to the expedition. However, several accounts have been written within broader contexts. They are clearly based on the formal records of the expedition (including many detailed daily radio reports from the "ice") now housed in Record Group 126, "Records of the US Antarctic Service," National Archives and Records Administration, in Suitland, Maryland, together with interviews with participants.

LISLE ROSE

See also **Antarctic Peninsula; Byrd, Richard E.; Geopolitics of the Antarctic; German South Polar *(Schwabenland)* Expedition (1938–1939); Ronne Antarctic Research Expedition (1947–1948); Ross Ice Shelf; Siple, Paul**

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UNITED STATES (BYRD) ANTARCTIC EXPEDITION (1928–1930)

Fresh from his aerial feats over the North Pole in 1926 and the Atlantic Ocean in 1927, Richard E. Byrd turned his attention to organizing a major expedition to Antarctica. It was to have three goals. First was for Byrd to fly over the South Pole. Second was to explore the interior of Antarctica, especially the areas near Roald Amundsen's route to the South Pole. And third was to add to the scientific knowledge of Antarctica, in geography, geology, geomagnetism, and especially meteorology.

In planning for the expedition, Amundsen, Byrd's former rival for the North Pole, played an important role. Amundsen's knowledge of the area and conditions at the Bay of Whales persuaded Byrd to build his base near where Amundsen began his journey to the South Pole. Amundsen himself recommended that Byrd buy *Sampson,* a Norwegian whaler, as his flagship; this Byrd did, renaming it *City of New York*. Finally, Amundsen encouraged Martin Ronne, who had been on the 1912 expedition, to join Byrd and contribute his experience in the Antarctic as a resource.

The expedition challenged Richard Byrd as an organizer and a publicist. Costing more than a million dollars, this was the largest and most expensive expedition that had ever been mounted to Antarctica. Byrd purchased three airplanes and two ships, including a minesweeper, *Chelsea,* renamed *Eleanor Bolling,* in addition to *City of New York*. He contracted with two other ships to transport supplies and break through the ice. Besides recruiting volunteers, Byrd paid salaries for men with special and critical skills, such as pilots.

As he had done in his quest for the North Pole, Byrd organized the expedition as his own enterprise. He used his fame—what he called "the hero business"—to draw gifts of money, supplies, and equipment. Often, he received supplies from manufacturers in exchange for endorsements. Byrd also turned to people who had supported his North Pole expedition. John D. Rockefeller Jr. and Edsel Ford gave cash. News media paid for stories. *The New York Times* assigned a reporter, Russell Owens, to travel with the expedition and write stories that would be wired home for publication. Similarly, Paramount Pictures contracted with Byrd and sent two camera men on the expedition to film and create a documentary. Byrd named his base "Little America" and one of his airplanes *Stars and Stripes* to please the American public, even though Norwegians played important roles.

The massive expedition reached the Ross Sea and entered the Bay of Whales on December 28, 1928. Days of unloading supplies and building shelters followed. At first, the expedition tried to use Ford trucks to transport supplies from the shoreline to Little America. However, the trucks proved unreliable, and the expedition resorted to dogs and sleds. Three airplanes needed unloading and assembly. One was a three-engine Ford, which Byrd named *Floyd Bennett* in honor of his pilot of the North Pole flight, who had died in 1928. Because of its three engines, this was the plane that Byrd wanted to use for the long flight over the South Pole. Another one-engine Fokker, *Virginia,* was to be a plane for rescue and exploration. The third airplane, a one-engine Fairchild, named *Stars and Stripes,* had large windows for use in aerial photography. Captain Ashley McKinley, who had written a textbook about aerial photography in World War I, had charge of the camera to photograph the terrain over which the plane flew. To fly the planes, Byrd hired pilots Bernt Balchen, Harold June, Alton Parker, and Dean Smith.

Soon after landing on the ice, men began building Little America, a small town made of prefabricated buildings buried in the snow. Apart from an administration building and bunkhouse, the complex included three radio antenna towers, a mess hall, hangers for the airplanes, storage sheds, and a machine shop that contained the first generator of electricity in Antarctica. Telephone lines connected some of the buildings.

The base sheltered forty-two men of varying temperaments, skills, and backgrounds. Besides the four pilots, there were three aircraft mechanics, three radio operators, five dog drivers, a doctor, three surveyors, a tailor, a carpenter, news media experts, a cook, and general hands. Four scientists took part in the expedition. Leading the scientists was the geologist Dr. Larry Gould, who also was appointed second-in-command. William Haines and Henry Harrison had responsibility for meteorology, while Frank T. Davies was in charge of geomagnetism. In addition, Malcolm Hanson was the expert in radio studies. For meteorological studies and weather forecasts, the expedition relied on Haines. This expedition shaped the career of young Paul Siple. He had earned a place on the expedition by winning a national contest to have a Boy Scout on the expedition. Siple would join in Byrd's later expeditions and achieve prominence as a scientist.

Already in January 1930, airplanes served as instruments for geographical discovery. On January 27, Byrd and Bernt Balchen flew over Edward VII Land and discovered a mountain chain they named in honor of John D. Rockefeller Jr. Another flight in February enabled them to reach a new land that Byrd named Marie Byrd Land. Successful flights aside, danger and misfortune lurked. In March, the expedition lost *Virginia* when a windstorm destroyed the airplane while it was parked during a geological investigation of the Queen Maud Mountains.

During the Antarctic winter of 1930, attention focused on planning Gould's geological expedition to the Queen Maud Mountains and Byrd's related flight to the South Pole. Depots of supplies for the geological expedition, marked with bright orange flags, helped in finding the route south. Gould's party could radio news of the weather to Little America and could rescue the South Pole party in an emergency. Meanwhile, the plane would drop aerial photographs of the terrain in the distance to the ground party. Not until November 1929 did weather allow *Floyd Bennett* to drop the last depot of food and airplane fuel at the foot of Mount Nansen.

On November 4, 1929, Gould and five men with dogs and sleds set out for the Queen Maud Mountains. Two weeks later, Byrd, Balchen, June, and McKinley took off from Little America in *Floyd Bennett*. Loaded with the camera, food, and fuel, the airplane struggled to climb over the Liv Glacier. Frantically, the men threw bags of food off the plane and, aided by the lightening of the load and a fortunate updraft, lifted the plane safely. On November 29, *Floyd Bennett* circled the South Pole, dropped the flag of the United States, weighted with a stone from the grave of Floyd Bennett, and then returned to the depot at Mount Nansen for refueling. Gould and his men returned to Little America on January 19 after a journey of more than 2 months and 1500 miles (2400 km).

Exploratory flights and scientific investigations continued until the expedition left Antarctica on February 9, 1930. In the 13 months on the continent, the first Byrd Antarctic Expedition had carried out all of its objectives and more. Apart from the dramatic flight over the South Pole, Byrd and his men had made substantive achievements. They had proven that airplanes could fly to depots, refuel, and fly again. Their flights into the interior had found new mountains, which they named in honor of sponsors John D. Rockefeller and Edsel Ford. New land east of the 150° W longitude had been discovered and named after Marie Byrd. Using aerial cameras for the first time to develop maps, they had recorded nearly 150,000 m^2 (390,000 km^2). Gould and his party studied the geology of the Queen Maud Mountains and decided that they were related to the mountains of

Victoria Land. Meanwhile, at Little America, the men surveyed the outline of the Bay of Whales and conducted soundings for its depth. For 13 months, a continuous record of meteorological and magnetic observations had been maintained.

Probably the greatest accomplishment of this expedition was in sowing the seeds for the next. The news stories, the books, and the film *With Byrd at the South Pole,* which followed the expedition, stoked public interest in Antarctica. Byrd would depend on his own popularity and public interest in financing another expedition. Finally, Byrd and other explorers would draw on the lessons learned in using airplanes, radio, and motorized transport in the work of exploration and science.

RAIMUND E. GOERLER

See also **Byrd, Richard E.; Norwegian *(Fram)* Expedition (1910–1912); Siple, Paul**

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UNITED STATES (BYRD) ANTARCTIC EXPEDITION (1933–1935)

The second Byrd Antarctic Expedition followed largely the model set by the Byrd Antarctic Expedition of 1928–1930. Both expeditions succeeded without governmental funding. Both used airplanes, motorized transport, and radio on an unprecedented scale. The second expedition resettled the base of the first, Little America, near the Bay of Whales at the Ross Ice Shelf. Like the first, the second expedition deliberately created stories for the mass media. The differences were that the second had more scientific investigations and a nearly fatal undertaking by Admiral Byrd to winter alone in the interior of Antarctica.

According to Byrd, the goal of his second expedition was to answer questions of science and geography raised during the first one. The expedition sought to apply twenty different sciences, including biology, geology, glaciology, astronomy, geophysics, meteorology, and oceanography, to the region. In addition, Byrd and his men planned to add to the geographical knowledge of Antarctica by further exploring areas such as the Rockefeller Mountains and Marie Byrd Land, which were discovered during the first expedition. Finally, Byrd and his men intended to test and employ motorized transports more than previously.

Fundraising proved more difficult for the second expedition than the first. Many Americans suffered financially in the Great Depression that had begun in 1929. A return to Antarctica, especially one that featured science so prominently, did not have the dramatic and popular appeal of the first flight to the South Pole. A wealthy few—Edsel Ford, William Horlick, Jacob Ruppert, Thomas Watson, and the National Geographic Society—gave significantly. However, most cash contributions were made in small amounts and amounted to only about $150,000, little more than one-tenth of the cost of the expedition. Companies granted equipment and supplies, and universities loaned scientific equipment.

As in the first expedition, news and entertainment media proved critical on the financial front. Major investors were the Columbia Broadcasting System and General Foods. In exchange for financial support, Byrd arranged regular radio broadcasts from Little America—relayed through Buenos Aires, Honolulu, Long Island, and San Francisco—to homes in the United States. General Foods paid $100,000 for the opportunity to air commercials during the broadcasts while Americans listened to news from Antarctica in their living rooms. Byrd's publicist, Charles Murphy, accompanied the expedition to make certain that good stories were ready for broadcast. In addition, Byrd persuaded a reluctant Paramount Studios, which doubted the commercial value of another film about Byrd and Antarctica, to invest by offering more flights and more drama.

Like Byrd's first expedition, the second proved to be a massive enterprise. Byrd leased for one dollar a year from the US Shipping Board a steel cargo vessel, *Pacific Fir,* which he renamed *Jacob Ruppert*. From the city of Oakland, California, Byrd bought at public auction an old icebreaker, *Bear,* which had been involved in the rescue of the Greeley expedition in 1884, for $1050. This he renamed *Bear of Oakland*. Airplanes were fundamental to all of Byrd's expeditions, and he bought three airplanes and an autogyro, an early helicopter. One of the airplanes, named *William Horlick,* had two engines and served as the chief plane for exploration; the other two had single engines for shorter flights. The helicopter was for short survey. For ground transport, the expedition had more than one hundred dogs. However, the ships also carried two light snowmobiles presented by Ford, a tractor from the Cleveland Tractor Company, and three Citroen tractors.

The second expedition had more people—fifty-six—winter in Antarctica than the first. Even as scientist Larry Gould had been second in charge in 1928, Byrd appointed another scientist, physicist Thomas C. Poulter, as second-in-command and chief of the scientific staff. Other scientists included two other physicists, two geologists, a geophysicist, two meteorologists, and three biologists. In addition, the wintering party had pilots, dog drivers, tractor drivers, a photographer, a motion picture photographer, a publicist, a surveyor, radio operators, carpenters, a cook, and a medical doctor. Paul Siple, who had been a Boy Scout on the first expedition, joined again as chief of the biologists. Roughly one-third of Byrd's team had been with him earlier. Among the new members was David Paige, who joined as the artist of the expedition.

Ice and weather severely delayed the expedition. Storms delayed the journey from New Zealand to Antarctica. On January 17, 1934, Byrd arrived at the Ross Ice Shelf and his former base, Little America. Ice from the shelf had broken into the sea. Through the years, pressure ridges had formed and made the trail—dubbed "Misery Trail"—from the shore to Little America difficult. Unloading took more time than expected. Meanwhile, ice began cracking on the Ross Ice Shelf, and the men feared that Little America could fall into the sea. To store supplies in an emergency, they built another base farther inland, "Retreat Camp."

These difficulties changed one of the primary goals of the expedition: to set up a camp in the interior of Antarctica. The expedition had brought a prefabricated hut designed for three men—Mountain House—to bury in the snow at the foot of the Queen Maud Mountains, some 400 miles from the coast. From here, a team would spend the winter and record meteorological data. Byrd hoped this adventure and scientific "first" would supply stories to the news media and persuade General Foods to renew its advertising contracts.

The delays at sea and in unloading, and the coming of winter, caused Byrd to change the plan. The expedition lacked time to transport enough supplies for three men or even to reach so far into the interior. Instead, Advance Base was built 123 miles from Little America. Byrd decided also that only one person—Byrd himself—would remain there. Many, including sponsors, questioned this decision. Isolated by distance and the Antarctic night, one person at Advance Base would have no help in an emergency. To have the leader of the expedition away for 6 months threatened administration and planning at Little America. Nevertheless, Byrd insisted. At parting, he ordered that no one risk his life to rescue him.

On March 22, 1934, Byrd flew to Advance Base and began his lonely adventure. He settled into routines of tending instruments that recorded winds, temperatures, and snowfall; viewing aurora; and freeing air ducts of snow and ice. Other routines included playing phonograph recordings, cooking, reading, and even taking walks in the Antarctic night by following poles connected with ropes. As promised, Byrd upheld a schedule of radio communications with Little America, using Morse code because his transmitter lacked the power to send his voice.

Catastrophe almost happened on May 31, 1934, when Byrd fainted from carbon monoxide fumes. Byrd credited this to faulty ventilation of his oil stove and used it sparingly. Nevertheless, the poison had entered his body and he suffered from the carbon monoxide as well as the cold in his hut. Byrd reduced his radio schedule to Little America and aroused concern there. In mid-June Byrd encouraged Poulter to undertake a field trip from Little America to Advance Base through the Antarctic night as an opportunity to view aurora. After three efforts through darkness and over dangerous crevasses, Poulter led a team of three and reached Byrd on August 11. Two months later, Byrd had recovered enough to fly back to Little America. The adventure at Advance Base resulted in scientific data and a work of literature. In 1938 the harrowing account of Byrd's experience appeared as *Alone,* which has remained one of the classic books of polar exploration.

Less dramatic but just as important were the many other accomplishments of this expedition. It was the first to use motorized transport successfully to move people and supplies into the interior for scientific investigation. Another success was to use seismic equipment for the first time to measure the thickness of ice of the Ross Ice Shelf and on the Rockefeller Plateau. Biologists discovered lichens on Scott Glacier and in Marie Byrd Land. They studied the life history of the Ross Sea at the Bay of Whales as well as bird life. Among the geographical discoveries were that no strait existed between the Ross and Weddell seas; new peaks of the Queen Maud Mountains, the Rockefeller Mountains, and the Rockefeller Plateau were also discovered. They also successfully sketched the eastern edge of the Ross Ice Shelf. Geologists on motorized transport garnered evidence that the Ford Ranges were related to the mountains of the Antarctic Peninsula.

In other ways, also, this expedition had significance. For Byrd, the experience had been so physically challenging that he would never winter again in Antarctica, even though he returned in 1947 and 1955. It would also be one of the last expeditions to Antarctica that would be privately financed. Apart from Finn Ronne's expedition in 1947, the United States government would take responsibility for exploration and investigation in Antarctica. Finally, the expedition had importance for such members of the expedition as Finn Ronne and Paul Siple, who would return to Antarctica and further develop their own careers as explorers and scientists.

RAIMUND E. GOERLER

See also **Byrd, Richard E.; Ronne Antarctic Research Expedition (1947–1948); Siple, Paul**

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UNITED STATES EXPLORING EXPEDITION (1838–1842)

Although the United States Exploring Expedition included Antarctica as only a part of its broad area of endeavor—it also surveyed the entire Pacific Ocean from Chile to Australia, as well as much of the Pacific Northwest—it nevertheless mapped 1,500 miles of previously unexplored Antarctic coastline and was the first to determine, based on its continuous line of sightings, that Antarctica is a continent.

Led by Lieutenant Charles Wilkes, a hotheaded, 40-year-old New Yorker nicknamed "Stormy Petrel," the six-ship squadron comprising the Exploring Expedition, or "Ex. Ex.," as it was widely known, sailed from Hampton Roads, Virginia, on August 18, 1838. Its primary object was the promotion of commerce, including the major industry of Pacific whaling, by improving navigation, but the expedition was also charged with extending the bounds of knowledge where practicable. It was the first voyage of discovery paid for by the US government and the last circumnavigation made solely under sail.

Wilkes commanded the flagship of the Ex. Ex., the 700-ton sloop of war *Vincennes,* with a complement of 190. The 559-ton sloop of war *Peacock* (commanded by Lieutenant William L. Hudson, second in command of the expedition) had a crew of 130, while the 224-ton brig *Porpoise* (commanded by Lieutenant Cadwalader Ringgold) carried 65. Two pilot schooners, the 110-ton *Sea Gull* (commanded by Lieutenant Robert E. Johnson, who was succeeded by Passed Midshipman James W. E. Reid) and the 96-ton *Flying Fish* (commanded by Lieutenant Samuel R. Knox, who was succeeded by Lieutenant William L. Walker on the Antarctic cruise from Tierra del Fuego), each had 15 crew members. The 75-ton storeship *Relief* (commanded by Lieutenant Andrew K. Long) had a complement of 75.

The naval expedition numbered 83 officers and 346 enlisted men—most of them quite young—but also included two civilian artists, Alfred T. Agate and Joseph Drayton, and seven civilian scientists, known as "the scientifics": botanists William D. Brackenridge and William Rich; conchologist Joseph P. Couthouy; geologist James D. Dana; naturalists Titian R. Peale and Charles Pickering; and philologist Horatio Hale.

After stopping in Rio de Janiero, the expedition explored Tierra del Fuego, made an initial foray into the Antarctic, then cruised north along the western coast of South America and transited the Pacific via Tahiti and Fiji to Australia. After a layover in Sydney, a second thrust south to Antarctica was followed by further exploration of Australia, New Zealand, Fiji, Hawaii, and the Pacific Northwest. The squadron then crossed the Pacific for a third time, to Manila and Singapore, before doubling the Cape of Good Hope and sailing the length of the Atlantic to New York City, reached on June 10, 1842.

The expedition covered a total of more than 87,000 miles, visited 280 Pacific islands, and produced 180 meticulously drawn charts, more than any previous surveying expedition. Some of the charts were still being used as recently as the Second World War.

First Southern Cruise

The first of Wilkes's two penetrations south into the Antarctic was begun on February 25, 1839, dangerously late in the Antarctic summer to be heading into icy, unknown waters.

Unfortunately, the Ex. Ex. ships were remarkably ill suited for polar work. Their open gunports constantly shipped seas, and their hulls were not reinforced or sheathed, leaving them unprotected from blows sustained in the pack ice. Other flaws of the hastily reconfigured ships were literally covered up with several coats of fresh paint by unscrupulous naval shipyards. The ships' crews were likewise extremely poorly provisioned, and the men suffered badly, often being reduced by their shoddy clothing and boots to wrapping their feet in blankets to stave off wetness and frostbite.

After a rendezvous at Orange Harbor, northwest of Cape Horn, Wilkes divided the squadron into three parts. *Vincennes* and *Relief* were dispatched to survey the coast of Tierra del Fuego. *Peacock*—carrying Peale, the only time any of the scientifics sailed on an Antarctic cruise during the entire expedition—and *Flying Fish* were directed to sail southwest in an attempt to better Captain James Cook's southing record of 71°10′ S, which he made at 106°54′ W. (Despite becoming separated in a gale and enduring great privation, *Peacock* reached 68°05′ S, while *Flying Fish* attained 70° S.)

Wilkes embarked upon *Porpoise,* which sailed with *Sea Gull* south across the Drake Passage toward the South Shetlands to see how far they could penetrate the pack ice. Icebergs and dense floes stopped them as they approached the northern reaches of the Weddell Sea around the northeastern tip of the Antarctic Peninsula but not before they deduced—catching a whiff of sulphur as they sailed to leeward—volcanic activity at Bridgeman Island.

Facing the inevitability of oncoming winter, Wilkes ordered *Sea Gull* to return to Orange Harbor via volcanic Deception Island, where its crew spent a week in Port Foster, the island's flooded caldera, collecting biological and volcanic specimens. *Porpoise,* surveying the eastern end of the South Shetland archipelago, narrowly escaped wrecking on Elephant Island in fog on March 7.

With the exception of *Sea Gull,* which was lost with all hands off the coast of Chile shortly after departing Orange Harbor at the end of April, the squadron rejoined company in Valparaiso on May 17. The sluggish *Relief* was detached from the expedition and directed to depot supplies at Hawaii and Australia. After surveying the South Pacific, the remaining Ex. Ex. ships reconvened in Sydney in November.

Second Southern Cruise

After a month's recuperation in Australia, the four ships sailed south again on December 26, 1839, with Wilkes commanding *Vincennes*. Aboard was one of the first canine visitors to the Antarctic, a Newfoundland dog Wilkes acquired in Sydney and named after that port. Despite some modifications to the three naval vessels, including closing up the gunports, nautical men in Sydney widely opined that the American ships would not survive their Antarctic voyage.

Once again the squadron quickly became separated, and in early February *Flying Fish* gave up its search for the others and returned to New Zealand alone.

The three larger ships managed to meet up, however, and on January 16, 1840, land was reported from *Peacock*'s masthead in the region of 157° E, although the sighting was, critically, not entered into the ship's log by Hudson. More landfalls were made in the following days.

Peacock narrowly escaped being wrecked on January 24 while on its own, when the ship was repeatedly blown backwards onto an ice floe, smashing its rudder. After pack ice floated in and trapped the ship, the crew was forced to drag *Peacock* through a narrow lead to open water, reached only after more than 24 hours of continuous effort. Upon return to Sydney for repairs in late February, it was found that the ice had battered parts of *Peacock*'s stem to a thickness of little more than an inch.

Aboard *Porpoise,* meanwhile, the tricolors of the two French exploration ships commanded by Dumont d'Urville were sighted on January 30. Due to a misunderstanding of intentions, however, the French and Americans failed to pass within hail, each side sailing away believing that the other had snubbed it.

After the American ships separated, *Vincennes* continued westward, sighting and charting discoveries until an icy barrier blocked his path. Wilkes named it Termination Land, marking as it did the end of his southern explorations; today it is known to be part of the Shackleton Ice Shelf.

Having followed the Antarctic coast for nearly 1500 miles, Wilkes announced the discovery of the Antarctic continent upon his return to Sydney on March 11.

Legacy

By the time the Exploring Expedition returned to New York in 1842 (minus *Flying Fish,* which was sold in Singapore, and *Peacock,* which foundered while trying to cross the bar at the mouth of the Columbia River in Oregon Territory), Wilkes' Antarctic discoveries were already being questioned. James Clark Ross, leader of the British Antarctic expedition of 1839–1843 in *Erebus* and *Terror,* to whom Wilkes gave a manuscript copy of his tracing of the Antarctic coastline, announced that he had sailed over positions that Wilkes laid down as land on his chart. Ross was equally dismissive of Wilkes' claim for an Antarctic mainland, but Wilkes insisted that he had indeed delineated a continent.

Subsequent investigations have proven the accuracy of most of the Exploring Expedition's delineation of the 1500 miles of Antarctic coastline it followed. Antarctic atmospheric conditions sometimes combine to create a phenomenon known as "looming" or superior mirage, in which geographic features beneath the horizon—as far as hundreds of miles distant—appear much closer than they are in reality. Wilkes was hardly the last Antarctic explorer to be misled by the occurrence, and aerial photo-mapping has confirmed the integrity of his Antarctic cartography.

The US Ex. Ex. represented a "coming of age" for science in the United States. Not only was the expedition federally funded, but it also gathered such a mass of material—in aggregate, some 40 tons (although very little was collected in the Antarctic)—that the government was forced to create an organized collection to manage it. The expedition's 4000 animal specimens, 50,000 botanical specimens, and thousands of shells, corals, fossils, and rock samples, along with 5000 ethnological and archaeological objects, became the foundation of the Smithsonian Institution, the national museum of the United States.

Jeff Rubin

See also **British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); Dumont d'Urville, Jules Sebastien Cesar; French Naval (*Astrolabe* and *Zélée*) Expedition (1837–1840); Ross, James Clark; Wilkes, Charles**

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UNITED STATES NAVY DEVELOPMENTS PROJECTS (1946–1948)

"Operation Highjump," formally designated the United States Navy Antarctic Development Project of 1946–1947, was described by its nominal leader, Rear Admiral Richard E. Byrd, USN (ret.), as "the largest exploring expedition ever organized," and it remains so to this day. Between the end of December 1946 and early March 1947, 4700 men in 13 ships divided into three groups—each built around either an aircraft carrier or a seaplane tender—mounted a comprehensive and benign assault on what remained the world's last "secret land."

In the rapidly maturing Cold War environment of 1946, the US government stated flatly that Operation Highjump was to be "primarily of a military nature," its chief objective "to train naval personnel and to test ships, planes, and equipment under frigid zone conditions." As such, it would be the first officially sponsored US Antarctic expedition since Charles Wilkes had sailed south more than a century before. Soviet observers were quick to recognize Highjump's significance. The official naval journal *Red Fleet* asserted that "US measures in Antarctica testify that American military circles are seeking to subject the [polar] regions to their control..."

While the charge was far from precise, it was not baseless. The Pentagon, already thinking about and planning for a possible Third World War, realized that polar combat would be an important element in any conflict with the Soviets. The US Navy had already conducted carrier operations in the Davis Strait, west of Greenland, the previous summer. While the long-standing question of formal US claims to the Antarctic continued to be held in abeyance, the Navy was eager not only to keep itself before the American public through spectacular exploits, but also to try out wartime technologies, especially the trimetrogon camera capable of overlapping aerial photography that could readily be translated into accurate maps. Byrd and the polar community were no less eager than the Navy to apply this new technology to their Antarctic playground.

Penetrating the ice-choked Ross Sea with great difficulty, the Central Group under Admiral Richard Cruzen finally reached Byrd's old base at the Bay of Whales in the Ross Sea in mid-January and established Little America IV. Despite the presence of the icebreaker *Northwind,* the thin-hulled cargo and communications ships found the going so slow and rough through the ice pack that Cruzen at one point panicked, cabling Byrd that the entire operation should, in effect, be cancelled and all the ships withdrawn well before the end of the austral summer. Byrd overruled him, gently but firmly. At the end of January, with a temporary tent city well on the way to completion, Byrd and his party flew in from the carrier *Philippine Sea* in half a dozen R4D (DC-4) transport planes. Although small by contemporary standards, the aircraft would never have made it off a carrier deck or on and off an ice runway without special ski-wheel devices and JATO (Jet Assisted Take-off) bottles strapped to the wings. Once the foul weather cleared on February 7, the R4Ds began a frantic 200-hour aerial mapping campaign of the adjacent Marie Byrd and Victoria Land coastal and inland areas, together with flights down the Ross Ice Shelf to the Transantarctic Mountains and the polar plateau beyond. On February 15, Byrd himself made a nostalgic second flight to the South Pole, though it was not entirely frivolous because of the trimetrogon mapping cameras. Altogether, the R4Ds at Little America were able to make twenty-nine flights despite the increasingly chancy weather of a waning Antarctic summer and early fall.

Meanwhile, the Eastern Group (Captain George Dufek) and the Western Group (Captain Charles Bond), centered around the seaplane tenders *Pine Island* and *Currituck,* respectively, sailed around roughly 70% of the Antarctic coast. Despite one horrific crash of a big Martin seaplane from the Eastern Group very early—killing several crewmen and necessitating a dramatic rescue effort—Dufek and Bond together managed to get off a further thirty-five mapping flights. On one of the flights, Lieutenant Commander David Bunger of the Western Group, winging along the Queen Mary Coast of Wilkes Land, suddenly came upon what seemed a polar fairyland "of blue and green lakes and brown hills in an otherwise limitless expanse of ice." Other such areas—most notably the Dry Valleys west of McMurdo Sound—were either known or would later be found dotting Antarctica, but "Bunger Oasis" generated understandable awe.

In the midst of these flights, the Navy and a small cadre of civilian and military scientists, including such veterans of previous Byrd expeditions as Paul Siple, "Bud" Waite, and Vernon Boyd, conducted a variety of equipment tests and scientific observations. Several penguins were seized for leisurely research back home, and weather observations, oceanographic readings, and geological samples were taken while the Navy tested survival suits and amphibious tracked vehicles on both land and water. In the waning days on the ice, Boyd led a rushed and daring land excursion out to Mount Helen Washington in the Rockefeller Range, some 150 miles (240 km) east of Little America, using two 16-ton tracked vehicles. The very short stay, however, frustrated the scientists, who complained bitterly that naval and military requirements and desires constantly overrode invaluable polar science.

Deteriorating weather and ice conditions forced Byrd to order the cargo and communications vessels out of the Bay of Whales as early as February 6, even as the R4D flights continued. Little America was hastily evacuated by the icebreaker *Burton Island* 17 days later. The Eastern Group and Western Group, not having to worry about getting out of a vast, ice-filled bowl like the Ross Sea, were able to continue their work several weeks longer. By early March, however, they were gone.

Byrd and his commanders believed that their aerial photographic missions had taken giant strides in unlocking the geographical and geophysical structure of Antarctica, and in some ways they had. Doubtless the signal achievement was proving through comprehensive observation that the Transantarctic Mountains were a single system bending around in an arc from Victoria Land to the Horlick Mountains and eastward to the Thiel Mountains.

Quite soon, however, photo experts suggested that Highjump was not the success its commanders had hoped. Claims of the amount of territory actually seen and photo-mapped had to be dramatically scaled down; worse, what was actually seen and photographed and where it was often proved difficult to determine under careful analysis. Years later, it would become apparent to one alert observer that "Through lack of ground control, more than half the photographs were of no value." Further confirmatory on-site work would be required to establish a "ground truth" sufficiently precise to make authoritative maps.

Byrd and his colleagues, led by Paul Siple, immediately agitated for a Highjump II. In the event, the Navy settled for a far more modest "Second Antarctic Development Project" the following austral summer (1947–1948), informally known as "Operation Windmill." It was an apt description, for the Navy employed yet another new technology, the helicopter, in an attempt to salvage the Highjump photographic record. Embarked on the icebreakers *Edisto* and *Burton Island,* the small, crude, first-generation Bell choppers were a mixed success at best in putting survey parties ashore to carefully triangulate known points. Starting late in the season just west of Bunger Oasis, the vessels and their aircraft ran into frequent storms and heavy ice. Survey and geological parties did get ashore at several points. They dramatically lessened the importance of the Oasis, which on the ground proved to be almost lifeless, and they managed to complete some good survey work west of the Ross Sea. East of Little America (which the vessels visited briefly at the end of January), however, deteriorating conditions effectively ended the operation before it could confirm or modify more than a fraction of the Highjump aerial record. Only the kind of permanent and widespread occupation of the continent first undertaken during the International Geophysical Year a decade later and carried forward by Operation Deep Freeze and similar foreign programs would realize the ambitions first set forth in the US Antarctic Development Projects.

LISLE ROSE

See also **Antarctic Accounts and Bibliographic Materials; Antarctic: Definitions and Boundaries; Byrd, Richard E.; Geopolitics of the Antarctic; Ross Ice Shelf; Siple, Paul; South Pole; United States Exploring Expedition (1838–1842)**

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VEGETATION

The terrestrial vegetation of Antarctica comprises five major groups of organisms: phanerogams (seed-producing flowering plants); and the spore-producing bryophytes, lichens, algae, and blue-green algae or cyanobacteria. In the strict sense, lichens and cyanobacteria are microorganisms rather than plants. However, the severe climate and growing conditions, particularly with very low temperatures, critically during the summer, combined with oceanic isolation from the other Southern Hemisphere land masses, thereby reducing immigration, considerably restricts the diversity of the Antarctic flora. Despite the great land mass (c. 14 million km^2) of the continent and its offshore islands, barely 1% is ice free, and of this very little provides favourable habitat for plant colonization. Much of it comprises wind- and ice-blasted rock faces and boulder fields, mineral soils rendered unstable by freeze–thaw action and erosion, substrates that rarely receive liquid water, coastal areas colonized by huge populations of penguins, and, beyond the Antarctic Circle, increasingly cold, dry, and sunless (in winter) landscapes with increasing latitude. Comparable environments in the High Arctic do not experience such severe growing conditions. There, the short summers are relatively warm, the permafrost thaws, there is generally no shortage of water, and the landscapes are connected to more southerly continental land masses, allowing unrestricted migration of flora and fauna northwards. This has led to a wide range of ecosystems with diverse plant, mammal, bird, insect, etc., biotas, and complex food webs and ecological processes. The significance of climate and immigration potential in determining the differences in biodiversity of the two polar regions is perhaps best exemplified by the distribution of flowering plants. In the Antarctic there are only two species, the pearlwort *Colobanthus quitensis* (family Caryophyllaceae) and the hair grass *Deschampsia antarctica* (family Poaceae), both reaching 68°42′ S. By comparison, more than 1000 species exist at this latitude in the Arctic, with almost 100 species extending to the northernmost extremity of land at 84° N in Peary Land.

Phytogeographic Zones

The Antarctic has been variously divided into biological regions or zones. One of the most commonly used systems for terrestrial organisms is based on the distribution of plants, and in particular that of the phanerogams, which is a direct response to the prevailing summer climate. Thus the maritime Antarctic region comprises the western Antarctic Peninsula and island groups to the north (South Shetland, South Orkney, and South Sandwich islands, and Bouvetøya). Here the milder, wetter climate permits the occurrence of *Colobanthus* and *Deschampsia,* as well as a wide range of bryophytes, lichens, algae, and invertebrates, including the only two Antarctic higher insects. The colder, drier continent and the eastern Antarctic Peninsula together comprise the continental

Antarctic region where flowering plants are absent and the diversity of other flora is greatly reduced. The sub-Antarctic zone to the north of the maritime Antarctic includes those islands (South Georgia, Prince Edward Islands, Îles Crozet, Îles Kerguelen, Macquarie Island, Heard Island, and McDonald Islands) with a much richer flora and fauna (especially flowering plants and invertebrates), greater range of communities, and greater complexity of ecosystems processes (notably peat formation and microbial decomposition) and trophic levels. Here, depending on the area of the islands, extent of ice cover, distance from other land masses, climate, etc., the number of higher plants varies from about ten to about forty, excluding many introduced species that have persisted. Unlike the cool, temperate islands lying well to the north of the Polar Front (e.g., Gough, Amsterdam, Campbell, Auckland), the sub-Antarctic islands do not possess any arboreal vegetation.

Impact of Climate and Climate Change on Antarctic Vegetation

The biological groups and their species composition in the Antarctic are, to a large extent, dependent on the past and present climate. Those species that succeeded in reaching the southern polar regions had to be physiologically preadapted to colonize and survive the severe environmental conditions (notably low summer temperatures, long periods of desiccation, high levels of solar irradiance and ultraviolet radiation, long winters, a short summer growing season, long periods of winter darkness, and continual summer daylight south of 67° S). Such conditions become progressively more extreme with increasing latitude. Survival and spread are dependent on the physiological tolerance of the plants and on relatively stable environmental conditions. However, much of the Antarctic, like most other biomes of the planet, is experiencing climate change. From a biological point of view, particularly on land, the increasing air temperatures that have been occurring since the middle of the twentieth century have had a significant impact on the state of the environment, and hence of plant habitats. Regional climate change has been greatest in the maritime Antarctic, where the mean annual temperature is now 1°C–2°C higher than it was 50 years ago, much of this increase occurring since the mid-1980s. Although only a relatively small change, it has had a significant impact on the rate of melting in spring and summer, resulting in the break-up of ice shelves and the rapid retreat and thinning of glaciers and ice caps. On land this has created more extensive glacier forelands, and new surfaces are becoming exposed through permanent ice. On Signy Island, South Orkney Islands, for example, about one-third of the ice cover has disappeared, and the glaciers and ice cap have thinned by up to 15 m since about 1970. Such changes are much more localized in continental Antarctica. Loss of ice cover creates new surfaces for plant colonization.

Vegetation History and Immigration

The Antarctic flora and vegetation appear to have remained remarkably unchanged throughout the past c. 5000–10,000 years (i.e., since the end of the last major ice age). Palynological studies (analysis of pollen, spores, and fragments of plants in soil, peat, ice, and lake sediments) have so far indicated that no plants appear to have existed during the Holocene that do not occur there now. Nevertheless, it is likely that some species, especially the environmentally more sensitive bryophytes, may have become established and later extinct without leaving any trace of their existence. Many new immigrant species will have reached the isolated land mass of Antarctica and its offshore islands over the past few millennia to produce the diversity that now exists. Many species, including the two flowering plants, had colonized the maritime Antarctic by c. 5000 years ago. Radiocarbon dating of moss in peat deposits suggests that terrestrial peat-forming vegetation began development around 5500 years ago in the maritime Antarctic. Subfossil aquatic mosses of that age have also been found in maritime lake sediments (James Ross Island), while in continental Antarctica a sample has been dated at about 8500 years old (Clear Lake, Vestfold Hills). However, in many areas where no peat-forming vegetation ever developed, very sparse colonization by cold-adapted mosses and lichens probably occurred much earlier, shortly after ice-free habitats became available. Radiocarbon dating of the surface of moss turf in various sites exposed by receding ice on Signy Island, South Orkney Islands, has indicated that former vegetation was covered by advancing ice during several periods of colder climate over the past several thousand years. The vegetation was therefore exposed to several major climate-change events, lasting many centuries, which caused glacial advances and retreats. The last of these advances was the "Little Ice Age" that ended in the mid- to late 1800s, although there have been at least two minor advances in the twentieth century, lasting only a few years (1920s and 1940s). The gradual increase in species diversity with time is exemplified by two prominent moss species (*Polytrichastrum longisetum* and *Polytrichum piliferum*) that appeared on Signy Island in the mid-1980s. Both colonized newly exposed soil adjacent to a receding ice cap; neither was known from the archipelago previously, and one *(P. longisetum)* was new to the Antarctic. On Deception Island, South Shetland Islands, three species also previously unknown in the Antarctic (*Funaria hygrometrica, Leptobryum pyriforme,* and the liverwort *Marchantia polymorpha*) appeared on ash within a year of its being deposited by the 1967–1970 volcanic eruptions. All became extinct within a few years after the geothermal effect ceased, but *P. longisetum* colonized this ash at one site in the late 1990s.

The transoceanic immigration of plant propagules (any biological structure, spore, or seed capable of generating a new plant) is a continuous process and is dependent on atmospheric circulation patterns. Spores in particular are dispersed into the atmosphere at a source (southern South America, Australasia, or even farther afield). Under certain weather conditions they are swept to high altitude and carried over great distances. If such wind patterns reach Antarctica, dust particles and spores may be deposited over land, with only a very small proportion landing directly on an ice-free substrate suitable for colonization. However, most are inevitably deposited on ice and remain there in perpetuity, but some will eventually reach ice-free ground in melt water. Spores have a remarkable longevity and many are capable of germinating decades or even centuries after being preserved in ice or soil. The accumulation of viable propagules in the soil and ice is referred to as the propagule bank or reservoir, and occasionally propagules will germinate or develop to produce new plants if conditions are favourable for this. Very rarely a species new to the area or even to the Antarctic may appear. The composition of this reservoir of potential colonists can be shown by culturing soil at various temperatures in the laboratory and noting those species that grow. Larger, heavier propagules, such as seeds and viable plant fragments, cannot be transported by wind over long distances, but these are important in local distribution of species already established in the Antarctic. However, long-distance dispersal of these larger propagules does occur, if rarely, by their becoming attached to feathers and feet of some migratory birds, although few propagules ever reach the Antarctic by this means. Skuas and gulls, in particular, are believed to be responsible for much of the spread of the grass *Deschampsia antarctica* throughout the maritime Antarctic, as they often pull up rooted pieces of the plants for nesting material, sometimes from locations several kilometres from their nest. Skuas may also be responsible for introducing the liverwort *Clasmatocolea grandiflora* to its only known Antarctic location south of the South Sandwich Islands (Deception Island), where it is abundant over a few square metres at a geothermal site. Within this unique bryophyte stand is a skua's nest. The skuas probably make annual crossings of Drake Passage to and from Tierra del Fuego, where the liverwort is locally common.

Colonization, Succession and Community Development

Ice is an important repository of both propagules and nutrients, accumulated on and within it over long periods. As it melts, these are deposited along the receding ice margins, and, if the substrate is reasonably stable, colonizing organisms become established. This succession of organisms commences with imperceptible soil microorganisms (bacteria, cyanobacteria, unicellular algae, and fungi), followed within a few years by filamentous algae, bryophytes (principally mosses), and, at maritime Antarctic sites, occasionally the two flowering plants. Finally, after a decade or two (but much longer in dry continental locations), lichens become visible, although the complex process of the fungal component's "lichenizing" the algal component, or development from specialized vegetative propagules, will have been inconspicuously proceeding for many years before this stage is reached. During this microbial and plant succession an increasing diversity of invertebrates colonizes the soil as the amount of organic matter accumulates. Depending on the nature of the habitat these associations of organisms develop distinct communities, defined by the plant composition. Where several closely related communities develop, each differing because a specific environmental feature allows one or a few species to become predominant, the association of communities defines a particular ecosystem (e.g., fellfield, bog, moss turf bank, encrusting lichen, etc.). Recently created habitats resulting from ice recession are sparsely colonized in the early stages, but in time may become extensively covered by mosses and, in seepage areas, sometimes by mats of cyanobacteria (notably black *Nostoc commune* and pink-red *Phormidium* spp.). Wet, nutrient-enriched areas close to penguin colonies are typically colonized by stands of the green alga *Prasiola crispa*. As the terrain evolves, matures, and stabilizes, a range of ecosystems, each comprising several different but closely related plant communities, develops. Thus, wetter ecosystems (bog) support various moss-dominated communities, while drier ecosystems (fellfield) are typically dominated by various lichen-dominated communities.

Under a stable climatic regime, once the mature community typical of a particular suite of environmental conditions (soil or rock type, nutrient regime, water availability and drainage, microclimate, etc.) has developed, and one or a few species established as the dominants, the composition and status of the species is unlikely to change, unless some major circumstance happens to alter the equilibrium. Many species are sensitive to minor changes in the hydrological, geological, soil, and nutrient regime of their habitat. Thus, environmental changes result in ecological gradients, which are reflected in a sharp change from one community type to another, producing a series of narrow communities, often within a small area. Prominent examples in the maritime Antarctic include the abrupt change in vegetation from acid rock and soil (e.g., *Andreaea, Rhizocarpon, Usnea* spp., etc.) to calcareous marble and soil (e.g., *Schistidium, Syntrichia,* and *Caloplaca* spp.), and from the margin of melt streams (e.g., *Brachythecium austrosalebrosum, Bryum pseudotriquetrum, Sanionia uncinata, Warnstorfia sarmentosa*) through boggy seepage ground *(S. uncinata, W. sarmentosa, W. fontinaliopsis)* to dry fellfield (*Andreaea, Usnea,* and many crustose lichens). In continental Antarctica a common gradient from wet to dry substrata is accompanied by a sharp change from *Bryum* spp., *Ceratodon purpureus,* or *Schistidium antarctici* to a community dominated by the lichens *Buellia frigida, Pseudephebe minuscula, Umbilicaria decussata,* and *Usnea sphacelata*.

With the current trend of climate change, especially in the maritime Antarctic, new species may be expected to colonize and become components of established communities, while the status of some existing species may change, causing a shift in dominance. However, as yet there is little evidence of this.

RONALD I. LEWIS-SMITH

See also **Algae; Amsterdam Island (Île Amsterdam); Antarctic Peninsula; Antarctica: Definitions and Boundaries; Auckland Islands; Biogeography; Bouvetøya; Campbell Islands; Climate Change; Climate Change Biology; Colonization; Crozet Islands (Îles Crozet); Deception Island; Flowering Plants; Fungi; Gough Island; Heard Island and McDonald Islands; Ice Ages; Insects; Kerguelen Islands (Îles Kerguelen); Lichens; Liverworts; Macquarie Island; Microbiology; Mosses; Polar Front; Prince Edward Islands; Skuas: Overview; Soils; South Georgia; South Orkney Islands; South Sandwich Islands; South Shetland Islands; Volcanoes**

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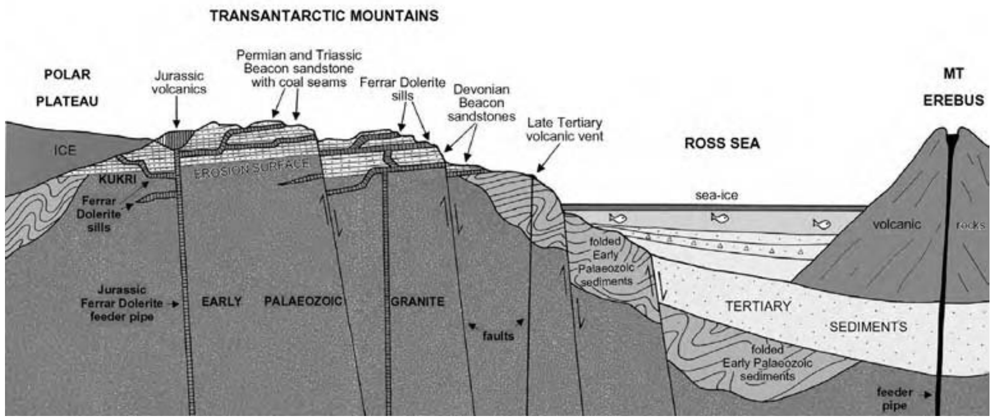
VICTORIA LAND, GEOLOGY OF

Introduction

Victoria Land straddles the northernmost segment of the Transantarctic Mountains adjacent to the Ross Sea. Uplifted in geologically young time, this mountain range provides one of the best-exposed geological sections in Antarctica. No wonder it was also among the first areas of Antarctica studied by geologists (David and Priestley 1914; Ferrar 1907).

Two rather different plate-tectonic events are responsible for the geological record in the area, the Paleozoic mountain-building process of the Ross Orogeny c. 500 Ma and the Cenozoic continental



Geological sketch map of Victoria Land. South Victoria Land and the Wilson Terrane (WT) of northern Victoria Land consist mainly of crystalline rocks and are of a similar character. The volcano-sedimentary Bowers Terrane (BT) and the turbiditic Robertson Bay Terrane (RBT) are unique to northern Victoria Land. The Rennick Graben (RG) is a geologically young feature related to the rifting of the Ross Sea.

split in the form of the Ross Sea rifting (40 Ma). In between, a tectonically quiet period is recorded by the deposition of terrestrial Gondwana sediments followed by extensive outpourings of plateau lavas.

The exposed rock sequence of the Transantarctic Mountains of southern Victoria Land (SVL) is thus comparatively simple, containing the following three subdivisions from bottom to top:

- A basement of metamorphic and granitic rocks of the Early Paleozoic Ross Orogen
- A flat-lying cover of the Devonian to Jurassic terrestrial Gondwana deposits
- A wide range of Cenozoic rift-related volcanic products

This simple sequence becomes more complicated in northern Victoria Land (NVL) because of additional low-grade fossiliferous terranes in the basement, an additional Mid-Paleozoic granite generation, and Cenozoic graben tectonics onshore.

On a geological map, the basement rocks of the Ross Orogen are exposed mainly on the lower slopes of the mountains in the form of a relatively narrow strip following the coast. In NVL, the exposed area is much wider. The cover rocks of the Gondwana sequence occur in a parallel strip further inland, mostly above 2000 m and close to the inland ice. These rocks show the regional tilt most clearly as the layers dip one or two degrees to the west. The young, rift-related volcanism occurs mainly on the Ross Sea coast with volcanic plateaus and small intrusions in NVL, stratovolcanoes around Terra Nova Bay and McMurdo Sound, and numerous small plugs in the areas in between. Some of the volcanoes are still active, like Mount Erebus on Ross Island.

The Basement Rocks of the Ross Orogen

During the Paleozoic, subduction processes similar to those under the present Andes formed a 3000-km-long mountain chain, the Ross Orogen of Antarctica. It consists of folded rock series that, under conditions of high temperature and low pressure, were metamorphosed (baked) to a varying degree and intruded by granitic bodies.

In SVL, the metamorphic rocks comprise a series of marbles, schists, metavolcanics, and intercalated gneisses with a general northwest strike and northwest-trending fold axes. These rocks are exposed east of the Skelton Glacier and in the foothills of the Royal Society Range and the southern Dry Valleys. Towards the north, they are replaced by gneisses. Granitic intrusions with generally calc-alkaline composition are present as local bodies in the entire area. The basement is made up completely of granitic rocks from Granite Harbour, which has given the name for the whole suite, northward into NVL.

In NVL, comparable basement rocks occur in the Wilson Terrane, the innermost of the three terranes (Bradshaw, Weaver, and Laird 1985) and the direct continuation of the SVL basement. In addition to shallow marine metasediments, there are also turbiditic deep-water series in the Wilson Terrane (e.g., in O'Kane Canyon, the Morozumi Range, and the Berg Mountains). High-grade gneisses and migmatites are present in the coastal areas from Terra Nova Bay to Mount Murchison (GANOVEX-ITALIANTARTIDE 1991) and along the west side of the Rennick Glacier from the Outback Nunataks to the Wilson Hills (GANOVEX Team 1987; Stump 1990). Granulite facies gneisses and migmatites are reported from the Campbell Glacier and the Wilson Hills. In the entire area of Victoria Land, the metamorphic rocks show two to four episodes of folding. Granite Harbour Intrusives in NVL are restricted to the Wilson Terrane.

The two outer terranes in NVL are of a very low metamorphic grade and contain fossils, the first Cambrian fossils found in Victoria Land (Laird et al. 1972).

The central Bowers terrane occurs in a narrow strip extending from the Pacific Coast to the Ross Sea. The exposed rocks form three major subunits (from bottom to top):

- A basal part of mainly submarine volcanics alternating with clastic marine sediments and partly volcanogenic turbidites
- Intermediate fossiliferous limestone–mudstone–sandstone–conglomerate sequences (Middle to Late Cambrian)
- A thick fluviatile to deltaic quartzite sequence at the top (Late Cambrian)

The top and bottom series are not directly dated. In suitable rock sequences the Bowers Supergroup is regularly folded (one episode), and the terrestrial quartzites form a box-like syncline more than 100 km long. The deformation in the basal volcanogenic sequence is more irregular.

The outer Robertson Bay Terrane contains a turbiditic sequence several kilometers thick. It is regularly folded around horizontal axes (one episode) and does not contain volcanic intercalations or coarse conglomerates. The turbidites are of distal character and contain sole marks and trace fossils. The base of the succession is nowhere exposed. The top may be present on Handler Ridge on the north side of Trafalgar Glacier, where large exotic blocks of limestone are found within the turbidite succession. These limestones have yielded a Lower Ordovician (Tremadocian) fauna of trilobites, conodonts, crinoids, brachiopods, and ostracods, so far the only occurrence of marine Ordovician sediments in Antarctica. The three terranes of NVL are separated by belts of schistose rocks several kilometers wide. The parent rocks in these schist belts can generally be correlated with rocks of the adjacent terranes. There is an additional phase of deformation in the schist belts. There is an ongoing discussion as to whether the outer terranes are far travelled or local products.

The Lanterman-Mariner suture forms one of the most interesting features in the basement geology of Victoria Land (Tessensohn and Ricci 2003). The suture as trace of an ancient subduction zone traverses NVL from the Lanterman Range to the Mariner Glacier and coincides with the Wilson-Bowers terrane boundary. It is accompanied by a number of peculiar features. A belt of high-pressure metamorphic rocks accompanies the boundary in the Wilson terrane. Flattened conglomerates in the Lanterman Range contain clasts of boninite, a rock type found in the vicinity of primitive oceanic island arcs. A belt of strongly sheared granitoids occurs in the Mariner Glacier area. Lenses of ultramafic rocks are found as tectonic slivers in both areas. Some of these lenses have an eclogitic core. All these features have been interpreted as being typical for a subduction zone. This was recently confirmed by the discovery of coesite (Palmeri, Talarico, and Ricci 2003) in samples from the eclogites. This high-pressure quartz modification requires a depth of formation of at least 90 km. The few other examples of coesite reported from a similar setting come from the Alps and the Himalayas.

The age of the metasediments in Victoria Land is poorly restricted. In the Skelton Glacier area, metasediments showing two phases of deformation are cut by a granite intrusion of 550 million years. This puts the parent rocks and an early deformation back in time before the Cambrian. In SVL, there are several other granites with a comparably early age. The main granite-forming igneous event in SVL and NVL took place around 500 Ma (510–480) at the boundary of the Cambrian and Ordovician periods. It was accompanied by widespread thermal metamorphism. A few late-stage bodies followed between 470 and 460 Ma.

Devonian–Carboniferous Admiralty Intrusives

These post-Ross, high-level intrusions with cooling ages of around 360 million years occur on all three terranes and also crosscut a terrane boundary (Mt. Supernal). The formation of this granite generation is not well understood, because in NVL there is no accompanying tectonic event. Similar rocks occur in Marie Byrd Land and Tasmania.

Gondwana Sequence

After the Ross period of mountain building, the rocks were eroded over a long period of time. The entire Silurian period is not represented. Erosion resulted in the formation of a peneplain cutting through the different units of the Ross orogen. The first new rocks laid down on this unconformity were Devonian sediments in SVL and subaerial volcanic rocks in NVL (Gallipoli Volcanics). The freshwater sediments containing fish remains and the first plants in Antarctica form the lowest horizon of the thick terrestrial Gondwana sequence that in Antarctica is called the Beacon Supergroup (Barrett 1971). The Gallipoli Volcanics in NVL are also associated with plant-bearing beds. The rocks are the surface equivalents of the coeval Admiralty Intrusives (360 million years).

The Carboniferous is missing in Victoria Land. The next sedimentary product in the sequence is a tillite (solidified moraine) of the Late Paleozoic glaciation, which, as fragments of Gondwana, affected all the southern continents.

The glacial beds are followed by mainly fluviatile sandstones with intercalated shaly horizons. The shales contain leaves of the *Glossopteris* flora represented on all southern continents. Large trees are preserved, sometimes in growth position. Coal seams several metres thick developed, sometimes very close above the glacial tillites.

The Triassic Beacon sequence does not differ fundamentally from the preceding Permian, but the *Glossopteris* flora are replaced by fernlike plants like *Dicroidium*.

Like on the other southern continents, the terrestrial Gondwana sequence provides a record of climate and environmental conditions for one of the largest land masses that ever existed on the planet.

The tectonically quiet sedimentation period lasted for a total of more than 200 million years. It came, however, to a rather abrupt end, when Gondwana started to break up in Jurassic times. An enormous event of lava production took place in southern Africa, Antarctica, and Tasmania. Lavas and pyroclastic rocks are particularly well exposed in the Rennick graben of NVL. In SVL, similar rocks occur at Carapace Nunatak. However, the main products preserved from this episode are the widespread Ferrar sills, horizontal sheets of lava intruded between the sandstone layers of the Beacon sequence. The sills are several metres to several hundreds of meters thick and are found across the entire continent, from Queen Maud Land to NVL.

Cenozoic Rifting

The extensional graben formation of the Ross Sea Rift during the Cenozoic is related to the final breakup process of Gondwana. The high Transantarctic Mountains can be regarded as the uplifted shoulder of the rift. With a summit elevation of c. 4000 m, they form the highest rift shoulder known on earth. With more than 10 km of sediments (Cooper and Davey 1987), the basins are also exceptionally deep.

The igneous activity related to the formation of the rift is alkaline in character, as in most other continental rifts on earth (e.g., the East African rift or the upper Rhine Graben) (Tessensohn and Wörner 1991). The volcanic Adare, Hallett, and Daniell peninsulas and Coulman Island were probably formed over the master faults along the northern Ross Sea coast in NVL. Stratovolcanoes are found where the coastline steps back to the west at Terra Nova Bay (Mt. Melbourne, Mt. Overlord) and McMurdo Sound (Mt. Erebus, Mt. Terror, Mt. Mourning, Mt. Discovery), probably due to the opening of transfer faults. Parallel to the northern one of these transfer faults, the Meander Intrusives form a series of alkali-granites, syenites, and gabbros, the only known Cenozoic intrusive rocks. The Malta Plateau north of Mariner Glacier consists of felsic peralkaline rocks. Other volcanic rocks occur in the coastal areas of Victoria Land in the form of small cones, vents, and plugs, on volcanic islands in the Ross Sea (Ross Island, Beaufort Island, Franklin Island, Possession Islands) and, as shown by geophysical surveys and in drill cores, in the western basin of the Ross Sea.

The oldest Cenozoic igneous rocks are the Meander Intrusives in NVL with ages from 25–38 million years. They are followed by peralkaline dikes (14–18 million years) and the peralkaline rocks of the Malta Plateau and other locations (7–11 million years). The basaltic plateaus are between 5 and 14 million years old, followed by the volcanic plugs and vents and the stratovolcanoes. However, all these age groups overlap each other to a certain extent. In SVL, volcanism starts around 19 Ma.

Structural Evolution

The Ross Orogen is the product of subduction of oceanic crust under the supercontinent Gondwana. Partial melting of the crust led to the formation of a magmatic arc, the Granite Harbour Intrusives. A pile of late Proterozoic sediments was deformed and metamorphosed during these processes. The former continent–ocean boundary is preserved in the form of a suture in NVL. On the oceanic side of this suture, two Cambrian terranes were accreted slightly later. After a tectonically quiet period, the first breakup event of Gondwana produced large volumes of plateau lavas and sills. Related to the final breakup split of Antarctica and Tasmania, the continental Ross Sea rift developed. A master fault between the Transantarctic Mountains and the Ross Sea led to down-faulting of the basins under the sea by more than 10 km and uplift of the Transantarctic Mountains by up to 4 km. The master fault and corresponding fault systems provided passageways for the young volcanism, which is still active today. A branch of the Ross Sea structures crosses NVL in the form of the Rennick Graben system, which has preserved the plateau lavas of the Mesa Ranges and brings down the Gondwana sequence almost to sea level.

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See also **Beacon Supergroup; British Antarctic *(Nimrod)* Expedition (1907–1909); British National Antarctic *(Discovery)* Expedition (1901–1904); Coal, Oil, and Gas; David, T.W. Edgeworth; Dry Valleys; Ferrar Supergroup; Fossils, Invertebrate; Fossils, Plant; Geological Evolution and Structure of Antarctica; Gondwana; Mount Erebus; Plate Tectonics; Priestley, Raymond; Transantarctic Mountains, Geology of; Volcanoes**

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VOLCANIC EVENTS

Antarctic volcanoes belong to the "Ring of Fire," a belt of volcanic systems surrounding the Pacific Ocean: Kamchatka, Japan, Philippines, New Zealand, Transantarctic Chain, Antarctic Peninsula, Andes, Galapagos, Central America, Rocky Mountains, and Alaska. The volcanic areas nearest to Antarctica are the South Sandwich Islands, South America, and New Zealand. Antarctic volcanic systems are located in the Antarctic Peninsula and in Victoria Land. The majority of the South Shetland Islands (Antarctic Peninsula) had a volcanic origin. Deception Island is a horseshoe-shaped caldera, still active (several eruptions occurred in 1967–1970), with several thermal springs, fumaroles, and steaming beaches. Mount Erebus (3790 m) is the largest of the four volcanic cones that form Ross Island. This volcano is fully active and the major historically known eruption occurred in 1984–1985. Mount Melbourne (2732 m, Northern Victoria Land) presently shows only weak geothermal activity.

Beyond local volcanism, Antarctica plays an important role in scientists' understanding of the climate–volcanism relationship, because the ice cap constitutes a natural archive of volcanic aerosols. The fact that the Antarctic ice sheet has a greater remoteness than even Greenland from active volcanic fields makes it more suitable for providing information on global events, potentially recording explosive volcanic eruptions that have occurred up to 20° N latitude. The explosivity of many volcanoes depends critically on the enrichment of volatile substances in near-surface magma reservoirs, where water (H_2O) and sulfur dioxide (SO_2) can form free gases at low pressure. During very explosive (Plinian) eruptions, more highly evolved derivative magmas are expelled with very high mass eruption rates (10^7–10^9 kg s^{-1}). Plinian eruptions form a spectacular column of the mixture of gas and particles, which forms a convective zone rising up to 40 km, because of the positive buoyancy in the atmosphere. Such eruptions inject ash and gases (mainly SO_2, HCl, and HF) directly into the stratosphere, where their residence time is up to 3 years, allowing their diffusion on a global scale. The photochemical reactions of SO_2 with H_2O and OH radicals in the stratosphere lead to the formation of micron- and submicron-sized sulphuric acid droplets. Depending on the geographical position of the source and the season of the year, volcanic aerosol layers form continuous veils (several km thick) at a height in the atmosphere of 20–30 km. Stratospheric sulphuric aerosol is a major forcing factor for climatic and environmental changes. It generally contributes to a cooling at the Earth's surface by solar radiation back-scattering and absorption. On the contrary, the absorption of sunlight and infrared radiation emitted by the Earth's surface causes a stratospheric warming. This radiative forcing results in massive changes in atmospheric circulation that, in turn, strongly affect tropospheric temperatures. Tropospheric and stratospheric temperature variations impact the climatic system by (1) changing midlatitude surface temperature with a possible seasonal pattern (summer cooling and winter warming) that depends on the eruption latitude, (2) causing differences in the temperature gradient between the equator and the poles and in the intensity and timing of the polar vortex, and (3) affecting climatic hemispheric conditions by variations of advective transport of air masses. Stratospheric sulphuric aerosol also changes the stratospheric chemistry, acting as a catalytic surface for heterogeneous reactions that change NOx into nitric acid and inactive anthropogenic chlorine reservoirs in the stratosphere ($ClONO_2$, HCl) into reactive chlorine (Cl, ClO). Such substances are effective in breaking up the O_3 molecule. The consequent ozone depletion constitutes a negative feedback of the surface cooling effect but heavily affects biota. A single volcanic eruption can perturb the climatic system with temperature changes on the same order of magnitude as other forcing factors, such as greenhouse gases and global anthropogenic sulphur emissions, but for shorter time periods. High-frequency volcanic activity could affect the climatic system for longer times (decennial to secular scale) and, if it occurs in climatically critical conditions, could act as a forcing factor, priming or speeding up climate mode changes via a positive feedback. In this view, the possibility of reconstructing a reliable volcanic history from ice-core stratigraphies of volcanic markers is highly relevant in assessing the climate–volcanism relationships.

Volcanic deposition the on Antarctic ice sheet can be revealed by detection of increased snow acidity, caused by deposition of acidic species such as H_2SO_4, HCl, and HF, or detection of sulphate levels anomalously higher than background values (tuned by biogenic emissions). In the former, conductivity measurements are carried out on melted (solution conductivity) or solid (electro-conductivity measurements [ECM]) ice-core sections, as well as by dielectric profiling (DEP) of solid ice. Specific measurements of sulphate (by ion chromatography) allow a better quantification of the volcanic deposition because sulphate is a conservative substance and is not affected by changes in snow acidity (e.g., neutralization processes with dust in glacial conditions) or interferences from other nonvolcanic conductive species. The direct measurement of sulphate allows a reliable estimation of the climatic impact of a volcanic eruption, independent of its explosivity. In fact, only the stratospheric sulphuric aerosol plays a relevant climatic role, ash having a short atmospheric residence time. The different sulphur concentration in the magmas is what is important, and small explosive events can inject more SO_2 into the atmosphere than large explosive eruptions. The El Chichon eruption (Mexico, 1982; 0.35 km^3 magma) emitted a very much larger SO_2 quantity than the Mount St. Helens eruption (USA, 1980; 0.5 km^3 magma), due to the larger concentration of sulphur in the magma (about 100 times larger).

Volcanism is recorded in ice cores up to a year after the relevant eruption, because of the time necessary for the sulphuric aerosol migration and deposition to the ice sheets. These peaks are correlated with temperatures deduced from oxygen isotope ratios in order to define climate connections.

The main advantages of a reliable reconstruction of the paleo-volcanism can be summarised as follows: (1) assessing the climatic and environmental impact of single major volcanic eruptions (mega-eruptions) and of high-frequency volcanic activity; (2) evaluating the stratosphere/troposphere interchange processes using stratospheric aerosol load as a marker; (3) using volcanic emissions to simulate other forcing factors, such as "nuclear winter" or meteoric impact; (4) setting and checking ice-core dating from seasonal marker stratigraphies or flow models by using volcanic signatures as known temporal horizons; and (5) synchronising the time scales of different ice cores (also in the different hemispheres) in order to understand whether climatic and environmental global changes occurred simultaneously in the two hemispheres or which hemisphere leads. This latest topic is very important in understanding driving forces and feedback factors of glaciation and deglaciation processes.

The cause–effect relationship between climate and volcanism is still controversial. On one hand, mega-eruptions or high-frequency volcanic activity seem to constitute a driving force for climate changes; on the other, the idea that the isostatic loading and unloading of the lithosphere, by accumulation and successive melting of the ice sheet, can generate instabilities in the Earth's mantle, and then volcanism, is an intriguing hypothesis.

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See also **Climate; Climate Change; Earth System, Antarctica as Part of; Geological Evolution and Structure of Antarctica; Ice Ages; Ice–Atmosphere Interaction and Near-Surface Processes; Ice Chemistry; Ice Core Analysis and Dating Techniques; Isotopes in Ice; Neotectonics; Ozone and the Polar Stratosphere; Paleoclimatology; Pollution Level Detection from Antarctic Snow and Ice; Precipitation; Snow Biogenic Processes; Snow Chemistry; Synoptic-Scale Weather Systems, Fronts And Jets; Volcanoes**

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VOLCANOES

Volcanoes are known from three areas within the Antarctic continent, and the oceanic islands in the surrounding Southern Ocean are mainly volcanic. Most of the volcanoes are extinct but there are a number that are considered active. The term "active volcano" usually applies to volcanoes that have erupted in historic times and have had their eruptions witnessed and recorded by people. As Antarctica was mainly unoccupied until the last 50 years, within Antarctica, active volcanoes are those that have had witnessed eruptions but also those showing evidence of recent eruptive activity. Evidence includes volcanic ash layers in the surrounding ice; very young ages (less than a few thousand years) determined on eruptive products; and geothermal features with temperatures above the ambient air. The following discussion is limited to the last 20 million years of geologic history, even though volcanism has occurred throughout the known geologic history of Antarctica.

In the Southern Ocean there are seventeen volcanic islands situated on the Antarctic tectonic plate. Big Ben volcano on Heard Island (53°06′ S, 73°30′ E) is active and lava was erupted on Marion Island (46°54′ S, 37°45′ E) in 1980. Eruptive columns were reported in the nineteenth century at the Balleny Islands (66°16′–67°38′ S, 162°15′–164°44′ E). St. Paul Island (38°43′ S, 77°33′ E) and Bouvetøya (54°25′ S, 3°21′ E) have fumaroles. Volcanic plumes were observed from the McDonald Islands (53°02′ S, 72°36′ E) during the 1990s and satellite images show a doubling of the size of the island between November 2000 and 2001.

Active volcanoes within the Antarctic continent occur in West Antarctica, the Antarctic Peninsula/ Ellsworth Land, and the western Ross Sea. Volcanoes in West Antarctica are found in Marie Byrd Land, where eighteen major and thirty small satellitic volcanic centers have been identified. The volcanoes occur in an intraplate tectonic setting and are on the flank of the West Antarctic Rift System, a region extending across West Antarctica through the Ross Sea in which the crust has been thinned by extension. Most of these impressive volcanoes are covered in snow and their bases are buried beneath the West Antarctic Ice Sheet. Mount Sidley (77° S, 126° W) is the tallest volcano in Antarctica at 4181 m high, rising 2200 meters above the surrounding ice level. Only Mount Berlin (76° S, 136° W) is considered active, as it has a steaming fumarolic ice tower and an underlying ice cave with elevated air temperatures. It is also the source of a 10,000-year-old and many older ash layers in ice on Mount Moulton (76° S, 135° W), a volcano 25 km to the east of Mount Berlin. Mount Takahe (76°15′ S, 112° W) has a youthful appearance, is 3460 m high, and appears to be the source of 7000-year-old volcanic ash in an ice core drilled at Byrd Station. There is also a possibility that an eruption is currently ongoing beneath the ice of the West Antarctic Ice Sheet. Airborne studies have shown a circular depression consistent with melting of the ice by a volcanic vent. The presence of a volcano beneath the depression is further evidenced by studies that show magnetic rocks typical of volcanoes.

In the western Ross Sea region, most volcanism occurs on or along the front of the Transantarctic Mountains and the volcanic rocks are known as the McMurdo Volcanic Group. Numerous magnetic anomalies detected beneath the Ross Sea are interpreted as small volcanic vents, but none of these vents is currently active. A very young-looking extrusive volcanic dome occurs among a group of volcanic cones and domes called The Pleiades (72°40′ S, 165°30′ E) on the Transantarctic Mountains in northern Victoria Land that probably erupted less than 1000 years ago. Fumaroles occur on a recently recognized active volcano, Mount Rittmann (73°28′ S, 165°37′ E), in north Victoria Land. Mt. Melbourne (74°21′ S, 164°42′ E), near Terra Nova Bay, has warm ground that steams near its summit, and an ash layer exposed in ice on the volcano's flank suggests that it erupted less than 200 years ago. Mount Erebus (77°32′ S, 167°10′ E) on Ross Island is the southernmost active volcano in the world and contains a persistent lake of molten anorthoclase phonolite magma. Small strombolian eruptions are common from the lake.

At the base of the Antarctic Peninsula and along the Ellsworth Land coast, eleven volcanic centers have been identified, but none of these volcanoes is currently active. Fourteen volcanic centers are known from the northern Antarctic Peninsula and adjacent offshore islands. Bridgeman Island (62°03′ S, 56°45′ W) has fumaroles and is here considered active. Seal Nunataks (65° S, 60°13′ W), on the east side of the Antarctic Peninsula, may be active but there are conflicting reports on the nature of the volcanic activity. Deception Island (63° S, 60°40′ W) lies at the southern end of Bransfield Strait, which is a marginal basin associated with subduction of the Pacific tectonic plate beneath the South Shetland Islands, which lie on the Antarctic tectonic plate. Deception Island is the second-most-active volcano in Antarctica, after Mount Erebus, and had significant eruptions in 1967, 1969, and 1970. The island is round, 14 km in diameter, and breached at the southeast end, allowing seawater to fill the large central caldera. Three new craters and an island were formed in the 1967 eruption. Volcanic ejecta were erupted from a fissure in ice on the caldera wall in February 1969 and resulted in significant meltwater and ice debris flows. A Chilean base was destroyed and a nearby British station severely damaged by the eruption. A chain of new craters was formed in August 1970 and the volcanic ejecta formed a strip of new land inside the caldera. Hot springs near the shoreline of the caldera provide a perfect location for swimming and bathing and have become a popular destination for tourists on tour ships.

Philip R. Kyle

See also **Antarctic Peninsula, Geology of; Balleny Islands; Bouvetøya; Deception Island; Heard Island and McDonald Islands; McMurdo Volcanic Group; Mount Erebus; Plate Tectonics; St. Paul Island (Île St. Paul); Transantarctic Mountains, Geology of; West Antarctic Rift System**

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VOSTOK STATION

Vostok Station, an inland station of the Russian Federation in Antarctica, was opened on December 19, 1957 to implement the USSR scientific program during the International Geophysical Year (IGY). The station was named after the sloop *Vostok*—one of the ships of the First Russian Antarctic Expedition of Fabian von Bellingshausen and M. Lazarev (1819–1821), and the first to see the Antarctic continent. The station is located on the Antarctic Plateau of East Antarctica at the point with coordinates 78°28′ S and 106°48′ E at a height of 3488 m above sea level. The distances from the coastal stations are: Mirnyy (Russia), 1410 km; Progress (Russia), 1350 km; Casey (Australia), 1360 km; Dumont d'Urville (France), 1705 km; Mario Zucchelli (Italy), 1470 km; and McMurdo (USA), 1305 km. The distance from Amundsen-Scott (USA) is 1250 km and from Dome C (Italy–France) is 620 km.

The choice of locality was determined by the plans for permanent helio-geophysical and aero-meteorological observations at the earth's South Geomagnetic Pole. The station coordinates corresponded to the pole position according to scientific knowledge of the time. The areas called "polar caps" in geophysics are situated around the geomagnetic poles in both hemispheres.

The magnetic field lines, along which the "solar wind" energy fluxes propagate, are directed towards the poles, leading to increased geomagnetic perturbation here. Organization of permanent observations of geomagnetism and the state of the ionosphere in "polar caps" make it possible to investigate the character of physical processes and internal relations in the "solar wind–magnetosphere–atmosphere" system. In the end, these data will explain the influence of solar activity and its variability on the formation of climate and weather conditions on Earth. The importance of these studies and a complicated character of cause–effect natural mechanisms of influence of the sun's physical state on the earth's atmosphere also necessitated continuation of research at Vostok station after the end of the IGY program. The choice of the station location proved to be especially successful, as in this area the largest of the known subglacial lakes on earth was discovered. It was also called Vostok.

Until 2005, Vostok and Amundsen-Scott stations remained the only year-round operating stations on the Antarctic continent. The annual logistics support of Vostok station (similar to its establishment in 1957) is by means of sledge-tractor traverses from Mirnyy station. Personnel, fresh products, and scientific equipment are delivered by airplanes from the coastal stations. An airstrip 3500 m long, which is suitable for receiving ski-equipped aircraft, including the LC-130 aircraft, is maintained at Vostok Station. In the late 1970s, the station was rebuilt. At present its structures include four buildings of aluminum panels, a glacial-drilling complex of veneer panels with heat insulation, an emergency electric power station (60 kW), and a base of fuel lubricants. Power supply is provided by three diesel generators with a capacity of 100 kW each. The station is capable of accommodating eighteen people in the wintertime and up to thirty in the summer. The telecommunications equipment is represented by satellite communication terminals and HF and UHF transceivers.

At Vostok, observations of geomagnetism, the state of the ionosphere, surface atmosphere, solar radiation, total ozone, and adaptation of the human organism are carried out on an annual basis. Until 1991, regular observations of the free atmosphere state (upper-air sounding) were conducted. During the seasonal period, the programs expand to include glaciological studies of ice cores from deep boreholes and snow–firn cover, study of the subglacial Lake Vostok parameters by geophysical methods (seismic sounding, seismology, radio-echo sounding), and geodetic methods (ice-cover dynamics, including drift and tidal motions), and studies of biodiversity of microorganisms at the station in the snow cover and ice cores. An important type of activity beginning from 1970 was deep ice-sheet drilling by specialists of St. Petersburg Mining Institute (SPMI). In 1998, drilling was stopped at a depth of 3623 m, as it was first necessary to develop an ecologically clean technology for penetrating the water layer of the subglacial lake. Such technology was jointly elaborated by specialists of SPMI and AARI and presented to the international community in 2002 and 2003 at XXVI and XXVII ATCM. As of June 2006, the borehole at Vostok station is the deepest of all boreholes drilled on the Earth's glaciers.

A complex of geophysical studies at Vostok is aimed at investigating the magnetosphere in the south polar cap of the planet. To assess its state, a universal PC-index was developed. Its application allowed derivation of a law that relates the PC-index value to the electric-field characteristics of "polar caps." A sharp increase in the PC-index shows the development of a magnetic substorm, making it possible to use it for operational prognostic purposes. It was determined that geomagnetic perturbations have a synchronous character at the magnetically conjugated points of the Southern and Northern hemispheres.

Thus, constant observations at Vostok Station allow a practical use of operational information in the northern regions of Russia.

The latitudinal and altitudinal location of Vostok Station determines its extremely severe climatic characteristics. Vostok is currently the "Pole of Cold" of our planet. The mean monthly air temperature ranges from –32.0°C (December) to –68.2°C (August), being above –60°C only for 4 months of the year (November–February), while its mean minimum values of below –70°C persist for 6 months (April–September). The absolute minimum air temperature ever measured on the planet was recorded at Vostok (–89.2°C on July 21, 1983). An absolute maximum of –12.2°C was observed on January 11, 2002. Relative air humidity throughout the year is close to 70%. Mean monthly atmospheric pressure varies between 618 mb (September) and 634 mb (January). Mean monthly wind speed is about 5 m s^{-1}, with the west-southwest direction predominating.

The discovery of the subglacial Lake Vostok resulted from comparison of the experimental data on seismic surveys, radio-echo sounding of the ice-sheet strata and the underlying surface character, and satellite altimetry of the glacial surface with theoretical thermodynamic models of the glacier. The outcome of this generalization was first presented at the SCAR Congress in Rome in 1994, and the first publication about this natural water body appeared in 1995. Beginning at this time, the RAE started comprehensive systematized studies of Lake Vostok. The lake presents an oblong knee-shaped water body elongated from north to south. Its length is 300 km, the width is 15 km, and the water table area is about 16,000 km^2. Its western shore is irregular, forming numerous bays and peninsulas, whereas the eastern shore is relatively rectilinear and precipitous. The southern lake area presents a deep water trough with a maximum water-layer thickness of 1200 m, while the northern area is shallow.

The maximum thickness of bottom sediments (up to 330 m) is observed in the deep-water trough. The ice-sheet thickness above the lake water layer changes from 3400 m in the southern part to 4350 m in the northern area. Directly beneath Vostok Station, the ice thickness is 3750 ± 25 m, the water layer thickness is 600 m, and the bottom-sediment thickness is 330 m.

Valerie Lukin

See also **Antarctic: Definitions and Boundaries; Bellingshausen, Fabian von; Climate; International Geophysical Year; Ionosphere; Lake Vostok; Russia: Antarctic Program; Russian Naval (*Vostok* and *Mirnyy*) Expedition (1819–1821); Solar Wind; South Pole; Temperature**

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WANDERING ALBATROSS

Wandering albatrosses *(Diomedea exulans)* are among the longest-winged flying birds with a wingspan of over 3 m. Wandering albatrosses weigh between 7 and 12 kg, with males about 20% heavier than females. Consistent with their feeding and flight characteristics, in addition to their long wings adapted for gliding flight, wandering albatrosses display massive pale bills and short tails. Adults have a characteristic white body and upper-wing plumage, the dark vermiculations diminishing with age. Juvenile birds have dark-brown plumage with white faces, their dark body plumage lightening with maturity.

Wandering albatrosses are a globally threatened species classified as "vulnerable" because of an overall decrease of 30% in numbers over three generations (70 years). Wandering albatrosses breed at five island groups (South Georgia, Prince Edward Islands, Îles Crozet, Îles Kerguelen, and Macquarie Island) with an estimated annual breeding population of 8500 pairs in this biennially breeding species. The total population is equivalent to about 28,000 mature individuals, with the Bird Island (South Georgia) and Crozet populations accounting for 30% of the species. These two populations indicated significant population decreases during the 1970s and 1980s, after which the Crozet population showed slight recovery before stabilising. The tiny population on Macquarie Island has recovered from precariously low levels to stabilise at the current level of about ten pairs breeding each year.

Wandering albatrosses return to their natal islands in November, about a month before egg laying. They are loosely colonial and breed in dispersed groups in open or patchy vegetation. The single egg is laid in a large truncated cone nest constructed of vegetation and mud. Laying occurs during December and February, and the parents share the 11-week incubation period. The chick hatches in March–April and is tended by the parents for 40 weeks before fledging occurs between November and February. The breeding season therefore for adults that successfully raise a chick extends over a 55-week period, requiring this species to be a biennial breeder, with no successful adults returning to breed the following year. Successful birds typically return to breed 2 years later, but some birds may elect not to return for 3–4 years. Unsuccessful birds usually attempt to breed in the successive year, but again some may defer for 2–3 years.

Most wandering albatrosses remain at sea for 5–7 years before returning to their natal island. Breeding generally commences between 8 and 11 years of age, although a decrease in the age of breeding has been reported for the decreasing Bird Island population. Birds from this population have also shown substantial reductions in both adult and juvenile survival rates, with longline fishing being implicated as the major source of the increased rates of mortality.

Wandering albatrosses forage widely over the Southern Ocean, and there is overlap in foraging distributions of birds from different colonies within the same ocean sectors. Typically, wandering albatrosses exploit sub-Antarctic and subtropical waters, and they forage over both neritic and shelf waters. Wandering albatrosses have minimal ability to dive and feed predominantly by surface-seizing their prey of fish and squid.

Wandering albatrosses are also prodigious scavengers and are perhaps the most aggressive of seabirds that forage on offal and discards behind fishing vessels. This propensity to scavenge during fishing operations makes them extremely susceptible to being drowned after ingesting baited hooks. Birds from South Georgia are likely to be most at risk from fisheries operating in the South Atlantic and Indo-Pacific Oceans, whereas the Îles Crozet, Prince Edward Islands, and Macquarie Island populations are likely to interact more with fishing operations in the Indian Ocean and Australian region. Widespread adoption of effective mitigation measures across a range of fleets is therefore required to safeguard the survival of this species.

Rosemary Gales

See also **Albatrosses: Overview; Antarctic Important Bird Area Inventory; Crozet Islands (Îles Crozet); Fish: Overview; Kerguelen Islands (Îles Kerguelen); Macquarie Island; Prince Edward Islands; Seabird Conservation; Seabird Populations and Trends; Seabirds at Sea; South Georgia**

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WEATHER FORECASTING

Weather forecasting for the Antarctic is becoming much less of an art and very much more of a science as knowledge of the various physical processes that occur in the Antarctic environment develops and as our armoury of forecasting tools increases. This said, the relative paucity of weather observations over Antarctica and the Southern Ocean, and an ocean–ice–atmosphere environment that results in weather varying from calm and sunny conditions to howling blizzards, present the forecaster with considerable challenges.

Most of the twenty-nine or so National Antarctic Programs have subprograms related to meteorology (COMNAP 2005), with some Antarctic stations having a forecasting role, for example Marambio (Argentina); Casey and Davis (Australia); Frei (Chile); Great Wall (China); Neumayer (Germany); Terra Nova Bay (Italy); Mirnyy (Russia); SANAE IV (South Africa); Rothera (UK); Vernadsky (Ukraine); and McMurdo (USA). However, for most Antarctic stations there is no dedicated weather forecasting service available on a year-round basis. Occasionally, in "winter," a station might request *ad hoc* forecasts to support a traverse or a similar venture. Usually, however, station activities proceed on the basis of station management, insisting that expeditioners take all possible care when going about their outdoor tasks and in particular keep their own close watch on the weather. During the "summer" period many stations have their numbers increased due to an influx of scientific and maintenance personnel. Field camps are established from which scientists conduct their research, aircraft are ferrying people and cargo between stations, ships, and field camps, and there is an increase in recreational activity by staff enjoying a break. This increases the demand for weather forecasts, and some stations issue routine forecasts through the summer period.

In preparing weather forecasts, Antarctic meteorologists use a variety of forecasting techniques. The mean sea level (MSL) chart (showing lines of equal pressure at mean sea level) is still a key forecasting aid. It shows the positions of centres of low- and high-pressure systems, the air-pressure gradient between them, and the location of frontal systems (boundaries between air masses with different characteristics). While routine observations of air pressure, air temperature, and wind speed and direction are essential for the preparation of the MSL chart, such synoptic data are sparse over Antarctica and the Southern Ocean. However, data from satellites do provide invaluable information for the construction of weather charts. The MSL chart becomes of less use just a few kilometres inland of the coast of Antarctica, where the terrain rises steeply. Normalising pressure to sea level is problematical over such a depth of the atmosphere (the average elevation is around 2000 m). Here the forecaster might resort to using streamline charts, which show the direction along which the air is flowing.

The forecasting task is four-dimensional, with the prediction of weather elements at some time in the future for a location in an atmosphere that has vertical and horizontal extent. Increasingly, the simple MSL chart is being supplemented or replaced by the output from numerical weather prediction (NWP). This has become a prime forecasting tool in Antarctica, as indeed it has worldwide. In the Antarctic context, NWP gives guidance from the broad-scale synoptic environment down to local weather phenomena affecting Antarctic stations. Paradoxically, while there are fewer conventional weather observations available in the Southern Hemisphere compared to north of the equator, the vast expanses of southern oceans coupled with the effectiveness of satellite data and the relatively simple orography in the Southern Hemisphere means that the NWP output from most global models is now of similar quality for each hemisphere.

NWP over Antarctica and the Southern Ocean may have some skill up to a week ahead, but terrain plays an important role in defining the surface wind flow over the Antarctic continent, and many operationally available computer models do not adequately resolve topographic and orographic features. While the NWP output might provide good general synoptic guidance, the accurate prediction of individual weather elements over the Antarctic continent is often the province of local knowledge and "nowcasting" techniques (in which extrapolation of observed trends is limited to the very short term). This is particularly the case in areas of steep or complex terrain.

Whatever the forecasting technique used, the main aim is usually to provide information that will increase the safety of humans in what is often a very hostile environment. A "blizzard" (where blowing snow reduces visibility to 100 m or less, the air temperature is freezing, and the surface wind speed is gale force or greater) is the archetypal Antarctic weather phenomenon. With strong winds and low temperatures comes "wind chill," the cooling of a person's body due to the combined effects of cold surroundings and wind carrying the heat away from the body. Antarctic explorers Paul Siple and Charles Passel first attempted quantification of wind chill in 1939. Another, more insidious phenomenon is that of "white-out," which occurs in uniformly overcast conditions over a snow-covered surface. It is associated with diffuse, shadowless illumination that causes a lack of definition of features on a snow surface. The resulting lack of horizon definition can make it difficult for a person to even walk safely, let alone operate vehicles or land an aeroplane. The prediction of white-out might be achieved by using NWP output to predict potential for cloudiness, supplemented with satellite imagery or direct human observations of cloud bands to extrapolate the movement of actual cloud features in the short term. NWP might also be used as a guide to the general environment for windy conditions. Often forecasts of snow drift will depend on a nowcasting approach (by considering whether snow has fallen recently and whether the forecast wind is strong enough to raise that snow to a sufficient height). Some decades ago operators in the Antarctic might have been forgiven for looking at the latest Antarctic forecast with a jaundiced eye. Nowadays, while it still pays to "hope for the best but prepare for the worst," improvements in understanding of the relevant physical processes, satellite data, and NWP mean that weather forecasting skill for the Antarctic (even for phenomena such as blizzards, wind chill, and white-out) are on par with forecasting for lower latitudes.

STEVE PENDLEBURY

See also **Field Camps; Ice–Atmosphere Interaction and Near-Surface Processes; Polar Lows and Mesoscale Weather Systems; Precipitation; Siple, Paul; Synoptic-Scale Weather Systems, Fronts and Jets; Temperature; Wind**

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WEDDELL, JAMES

Weddell was *primus inter pares* in the group of sealing captains who accomplished so much exploration of the Antarctic and sub-Antarctic in the early years of the nineteenth century, and whose achievements were recorded for posterity. During his great voyage of 1822–1824, he discovered the sea now named after him and penetrated it to the then-astonishing latitude of 74°15′ S.

As with so many of his contemporaries, much of Weddell's early life is obscure. His father was a prosperous Scottish-born upholsterer trading in London, and his mother, to whom he was deeply attached throughout his life, was a Quaker. Although it is known that he was born in 1787, his place of birth is uncertain. London would seem likely, but both Ostend and Massachusetts are possible. His father died early, and Weddell, following a brother into the Royal Navy, became a "boy, first class" on board HMS *Swan* on June 1, 1796. He was soon discharged and entered the merchant service, where he remained until he rejoined the Royal Navy in 1810 as an able seaman. Promotion then became rapid, as Weddell was a highly competent seaman. He was acting master within 1 year and received his warrant as master within 2. With the peace following the Napoleonic Wars, Weddell left the navy and reentered the merchant service.

After a few unremarkable years, Weddell arranged for the firm of Strachan & Gavin, of Leith, together with other investors—of whom one seems to have been Weddell himself—to outfit the brig *Jane* (160 tons) for sealing in southern waters, under his command. During his first voyage, in 1819–1820, Weddell—who, unusually for the time, carried a chronometer and knew how to use it—visited the South Shetland Islands, searched for and failed to find the "Aurora Islands," and wintered in the Falkland Islands, where he prepared detailed notes and charts of anchorages.

Encouraged by the success of the voyage, the investors purchased a diminutive vessel, *Beaufoy* (65 tons), to act as tender to *Jane,* and Weddell again set forth for the sealing grounds in 1821. He visited the Falklands, South Georgia, and the South Shetland Islands, and Michael McLeod, the captain of *Beaufoy,* reached the South Orkney Islands on a scouting mission a mere 6 days after their discovery by George Powell and Nathaniel Palmer. It seems to have been Weddell who named this archipelago when he visited it in *Jane* in February 1822. He charted the islands and, following his usual practice, made such scientific observations as he could.

By this time, Weddell was highly experienced in the sealing trade, and Strachan & Gavin, which seems to have had the same enlightened attitude as did the Enderby Brothers with regard to their captains engaging in exploratory and scientific work when possible, speedily decided on a third voyage. After a complete reequipping, *Jane* and *Beaufoy,* the latter under the command of Matthew Brisbane, who appears to have been an almost exact contemporary of Weddell, departed the Thames in September 1822. *Jane* sprang a leak on the voyage south, and this caused delays, as it was necessary to spend some time in a secure anchorage on the Patagonian coast in order to effect repairs. It became obvious to Weddell that it would not be profitable to head to the South Shetlands because of the lateness of the season and also because most of the seals in that archipelago had, by that date, already been slaughtered. He determined to aim for the South Orkneys, where they arrived after much bad weather, in mid-January 1823. Few seals were secured, but among them was one preserved by Weddell, which later became the type specimen of *Leptonychotes weddelli,* the Weddell seal. Unsatisfied, Weddell determined to seek new sealing islands and to examine the area between the South Shetlands and South Sandwich Islands. Failing in this, he decided to head south. For the first part of the passage the conditions were poor, but in mid-February, extraordinarily late in the season, and well to the south of the Antarctic Circle, the weather ameliorated and rapid progress was made in the desired direction. On February 18, the sea was completely clear of ice—in Weddell's words, "not a particle...was to be seen"—and these conditions continued with a favourable wind "light and easterly" enabling "all sail" to be kept. On February 20, the wind shifted to the south, causing Weddell to reverse course from his farthest south at 74°15′ S, 34°16′ W. No land was in sight.

It is important to appreciate the wisdom of Weddell's decision at this juncture. He was aware that a long and potentially difficult navigation northwards at an unpropitious time of the year awaited *Jane, Beaufoy,* and their crews. Even though further progress could have been made by altering course to southeast or west, Weddell appreciated that disaster loomed for his ships if the weather suddenly turned, as it could easily have done, and that, even if he did discover new sealing grounds, it was so late that most of the seals would already have left.

By mid-March both ships were in Undine Harbour in South Georgia, refitting and refreshing the crews, especially with regard to antiscorbutics, and continuing sealing. Weddell himself devoted much time on charting and making observations of wildlife and other natural phenomena. After wintering in the Falklands, Weddell set off, in October, on a renewed attempt to reach the South Shetlands. Although it was early in the season, this would have been at the optimal period for sealing, and the expedition had so far been woefully unsuccessful in its main aim. However, after a prolonged struggle with the pack, which was very far north, it proved impossible to land, and Weddell headed for Tierra del Fuego. During his sojourn there, he continued with his observations of wildlife, this time also experiencing the novelty of trying to establish relations with the inhabitants, in whom he appears to have had a good deal of interest.

By now anxious about the prospect of having to return home with no seal products, Weddell ordered that the two ships separate, and both thereafter ultimately had some success. *Jane* reached London in July 1824, to find that *Beaufoy* had arrived some weeks earlier.

Partly based on a desire to ensure that his record south be accepted by the maritime authorities, Weddell determined to prepare a book concerning his voyages. This appeared in 1825 under the ponderous title *A Voyage Towards the South Pole Performed in the Years 1822–1824; Containing an Examination of the Antarctic Sea to the Seventy-Fourth Degree of Latitude: and a Visit to Tierra del Fuego* and presented a distillation of his experiences, including comprehensive notes concerning navigation in the difficult waters. It also included his observations on wildlife and contained a proposal for the conservation of seals to ensure continuing future harvests. The book is a masterpiece, and recognition of his work came with his election to Fellowship of the Royal Society of Edinburgh.

Weddell's work at sea as captain of *Jane* continued but not as part of the sealing trade. *Jane* was deemed unfit for further use while at Horta in the Azores, and, after having been shipwrecked on the way home, Weddell became captain of *Eliza,* engaged in the Australia trade. One of the most celebrated coincidental meetings of polar "greats" took place in May 1831, on the Tasmanian coast, when Weddell and his men helped to moor John Biscoe's *Tula,* limping in with a sick crew after her great voyage.

For both Weddell and Brisbane, sad demises were in store. The latter was murdered by gauchos in the Falkland Islands on August 26, 1833. Weddell left the sea after returning from Tasmania in mid-1832. He resided in lodgings in London, where, despite being one of the greatest Antarctic sailors of all time, he died in poverty in September 1834.

Ian R. Stone

See also **Biscoe, John; Enderby, Messrs.; Sealing, History of; South Georgia; South Orkney Islands; South Sandwich Islands; South Shetland Islands; Weddell Seal**

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WEDDELL, ROSS, AND OTHER POLAR GYRES

The large-scale circulation in the Antarctic Ocean is dominated by the Antarctic Circumpolar Current (ACC) and the subpolar gyres to its south. Whereas zonal flow prevails in the ACC, the large-scale cyclonic subpolar gyres induce meridional flow at their eastern and western rims, westward flow in the southern parts adjacent to the Antarctic continent, and eastward flow in the north. The subpolar gyres are elongated in shape, extending 3000–4000 km zonally and 1500–2000 km meridionally. There are three major gyres: the Weddell, the Ross, and the Kerguelen, which differ in size, flow intensity, and water mass properties. The Weddell and the Ross gyres are related to, but extend well beyond, the large embayments in the Antarctic continent for which they are named. The existence and shape of the Kerguelen Gyre is still a matter of debate.

Flow in the gyres has been determined at specific locations by measurements from ships, buoys and icebergs, or sea-ice drift, and to a lesser degree with current meters. A more comprehensive view of the shape of the gyres has been derived from water mass property distributions. Numerical models of sufficient horizontal resolution also provide useful information on the shape of the gyres and their currents. However, significant parts of the boundaries of the gyres are not fixed by topographical features but by variable water mass transition zones, leading to different estimates of area, depth, and transport from source to source. Further uncertainty results from the southern boundaries of the gyres, where related flows extend onto the continental shelves.

The Weddell Gyre is the largest of the three, extending eastward from the Antarctic Peninsula to about 30° E. It includes the entire Weddell Abyssal Plain and about half of the Enderby Abyssal Plain. Its northern limit is closely related to the southern slopes of the South Scotia Ridge and the Southwest Indian Ridges located between 55° and 60° S. The strong southward bend of the Antarctic Circumpolar Current west of Conrad Rise leads to a water mass transition zone near 30° E, separating the warmer, more saline waters of the ACC from the cooler and fresher Weddell Gyre. Limited by ice-shelf fronts in the south and the oceanic Weddell Front in the north, the Weddell Gyre extends over 7 million km^2, more than twice the size of the Weddell Sea. Its mean depth is near 3900 m, with a maximum near 5600 m in the Enderby Basin. Water mass property distributions and models indicate two embedded subgyres, divided near the Greenwich Meridian, each having volume transports of 50–55 Sv (1 Sv = 1 million m^3/sec). Mean currents in the interior of the Gyre are only on the order of 1 cm s^{-1} but increase to 10–50 cm s^{-1} in the boundaries. Superimposed on the mean flows are mesoscale eddies with comparable velocities. Tidal currents are small in the interior of the gyres but larger over the continental slopes and shelves.

The Ross Gyre extends from the coast of Victoria Land north and east of the Ross Sea into the Amundsen Abyssal Plain. To its northwest the Gyre is bounded by the slope of the Pacific Antarctic Ridge. Its eastern boundary is often located near 130° W, but models indicate a further eastward extension to 90° W, sometimes called the Bellingshausen Gyre. West of 130° W, the Ross Gyre covers an area of 2.4 million km^2 and has a volume transport modelled at 35 Sv. Current velocities are similar to those in the Weddell Gyre; the mean depth is near 3000 m and the maximum 4600 m.

The Kerguelen Gyre extends eastward from the Kerguelen Plateau at about 75° E across the Australian Antarctic Basin, with a northern boundary along the Southeast Indian Ridge. Northwestward flow along the eastern slope of the Kerguelen Plateau clearly shows up in the water mass distributions. Information on its northern and eastern rims results from models, which indicate a gyre flow of 45 Sv. Its area is 2.6 million km^2, mean depth 3900 m, and maximum depth 4700 km.

The origin of the gyres is a combination of wind and thermohaline forcing and the constraints of a bottom topography that has evolved since at least the Jurassic period. Since water mass stratification is normally weak in the polar oceans, currents vary little with depth, allowing bottom topography to exert a strong steering effect on the flow. Exceptions include dense bottom water plumes that can descend the continental slope. Atmospheric forcing of the gyre circulations is related to the transition from westerly winds in the north to easterly winds near the Antarctic coast. This induces opposite directions of flow in the northern and southern limbs of the gyres, and upwelling (Antarctic Divergence) in between. The winds result from the low-pressure belt around the Antarctic continental high-pressure system. The regionally variable wind stress induces sea-surface slopes in geostrophic balance with the ocean currents. While the bottom topography forces northward meridional flows in the west, southward return flows on the eastern limbs are less clear for all three gyres.

The southern limbs of the subpolar gyres sometimes include the Antarctic Coastal Current, and these two flow regimes are often not clearly separated. The bottom inclination at the continental slope often gives rise to a jet-like westward current, in geostrophic equilibrium with density gradients (Antarctic Slope Front) between different water mass characteristics on the shelf and in the deep sea. The northern boundaries of the gyres coincide with the southern boundary of the ACC, also identified by a frontal region. This front can have a double structure, as in the Weddell-Scotia Confluence at the northwestern boundary of the Weddell Gyre, where waters from the Antarctic peninsula continental shelf are injected between those of the Weddell Sea and ACC. Farther to the east the Southern Boundary of the ACC is often called the Weddell Front.

Within the gyres, water properties result from intrusions coming from the Antarctic Circumpolar Current and modifications due the ocean–atmosphere–ice interactions. Circumpolar Deep Water intruding at intermediate depths from the north is relatively warm and saline and rises toward the surface inside the gyres to replace surface water moving toward the boundaries. In winter the surface mixed layer is near freezing (~–1.9°C), and sea-ice formation results in salt release. That brine increases the density of the mixed layer, leading to vertical convection that entrains the Circumpolar Deep Water below. This warms the mixed layer, increasing heat flux to the sea ice and atmosphere. Melting sea ice reduces the mixed-layer density, in turn retarding convection and ice growth, a delicate balance in a region of low vertical stability.

Even more salt is released at the southern edges of the gyres, or their extensions onto the continental shelves, where offshore winds move newly forming ice away from the coastline. This results in the formation of high-salinity shelf water, which is dense enough to sink along the continental slope. There it mixes with colder shelf waters freshened by melting under the large ice shelves, entrains deep water from the gyres, and at some locations becomes dense enough to reach the floor of the abyssal plains. During these processes this dense water with recently "ventilated" components also becomes entrained in the larger gyre circulations, eventually exiting them as Antarctic Bottom Water or in the lowest layers of Circumpolar Deep Water, spreading into the deep basins of the world ocean. The formation of bottom water and the upwelling of deep water in the subpolar gyres are major components of the vertical overturning circulation of the global ocean. The properties and intensity of deep and bottom water formation vary from gyre to gyre.

Deep ocean convection occurred within the Weddell Gyre west of Maud Rise in conjunction with a large and persistent polynya that occurred there in the mid-1970s. However, most modern deep-water modification and bottom water formation is related to processes that take place on the Antarctic continental shelves and slopes. Water mass properties and circulation are subject to decadal variations, with freshening observed during recent decades in the Ross Sea, while bottom water in the Weddell Sea shows a trend of warming and salinity increase. Deep water in the Weddell Gyre increased in temperature until the mid-1990s and has cooled since then. It is not yet clear whether this is in response to decadal variability (e.g., related to El Niño in the form of the Antarctic Dipole) or to trends related to global warming.

The gyre structures impact the sea-ice cover, with the widest sea-ice belts in the Weddell and Ross Sea areas. In the boundary currents the sea-ice thickness of several meters is clearly larger than in the interior of the gyres, where only 50–100 cm are measured. Sea ice is transported out of the gyres toward the north, where it comes into contact with the waters of the ACC and melts. Icebergs also drift in and add freshwater to the gyre circulations. Their drift tracks depend both on the wind forcing and on the compactness of the sea ice.

Although less productive than oceanic frontal regions, the subpolar gyres are also home to a diverse sea life. Various species of whales, seals, and penguins are found, with fish less abundant than around the sub-Antarctic islands. In the Weddell Sea the dominant demersal fish is *Chionodraco myersi* and the pelagic *Pleuragramma antarcticum*. In particular the sea ice accommodates important biota like krill, which utilize the ice cover as an effective overwintering strategy. The gyre flows and upwellings influence the life cycles of plankton and fish larvae.

EBERHARD FAHRBACH

See also **Amundsen Sea, Oceanography of; Antarctic Bottom Water; Antarctic Divergence; Antarctic Ice Sheet: Definitions and Description; Antarctic Peninsula; Antarctic Surface Waters; Circumpolar Current, Antarctic; Circumpolar Deep Water; Coastal Ocean Currents; Continental Shelves and Slopes; Ice Shelves; Icebergs; Polar Front; Polynyas and Leads in the Southern Ocean; Ross Sea, Oceanography of; Southern Ocean: Fronts and Frontal Zones; Thermohaline and Wind-Driven Circulations in the Southern Ocean; Weddell Sea, Oceanography of**

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WEDDELL SEA, OCEANOGRAPHY OF

Discovered and named the George IV Sea in 1823 during a seal hunt on *Jane,* the Weddell Sea was renamed in 1900 for the master of that ship, James Weddell (1787–1834). Nearly 100 years later, Wilhelm Filchner reached the southern coast of the Weddell Sea onboard *Deutschland,* while attempting to determine if Antarctica was a single continent. The Weddell Sea is the southernmost extension of the South Atlantic, indenting Antarctica between the Antarctic Peninsula (~60° W) and Coats Land (10°–35° W). Its southern boundary extends beneath the Filchner-Ronne Ice Shelf, and its northern boundary follows the course of the South Scotia Ridge, extending along ~60° S from the tip of the Antarctic Peninsula to the South Sandwich Islands (30° W). If a line from there to Kapp Norvegia (10° W, 71° S) is taken as the eastern boundary, then the Weddell Sea covers an area of 2.8 million km^2, slightly larger than the Mediterranean Sea, and has a volume of 7.6 million km^3, ~0.5% of the world ocean. A boundary at the eastern end of the Weddell Gyre would encompass a greater area and volume.

At depths >4000 m, the Weddell Abyssal Plain is the deepest portion of the Weddell Sea. It is fringed by a relatively steep (15°–30°) continental slope, carved by numerous marine canyons connecting the abyss with the >500-m-deep continental shelf. This depth is greater than the 200 m typical for continental shelves worldwide and is caused by the load of the Antarctic Ice Sheet. The shelf width ranges from 0–50 km in the east and ~500 km in the south to ~100 km in the west, with a coastline running along the fronts (or grounding lines) of the Riiser-Larsen, Brunt, Filchner-Ronne, and Larsen ice shelves. Two major troughs (Filchner and Ronne) with maximum depths >1200 m have been cut into the southern continental shelf, marking the northward advance of the Antarctic Ice Sheet during glacial times. These troughs and a southward-sloping sea floor support the exchange of water masses between continental-shelf and ice-shelf cavities. Confined by the bottom relief, the ice-shelf base, and the continental margin grounding lines, the Filchner-Ronne cavity is the largest in the Southern Ocean, containing 0.14 million km^3 of water. The flow of waters of circumpolar origin into the Weddell Sea is disturbed by a 1600-m seamount, Maud Rise, centered at 65° S, 2.5° E. The chain of islands (South Shetland

Islands, South Orkney Islands, and South Sandwich Islands) along the South Scotia Ridge is interrupted by gaps as deep as 3000 m, allowing for the escape of dense Weddell Sea waters into the Scotia Sea.

The Weddell Sea climate is influenced by the northward flow of cold continental air and the transit of synoptic low-pressure systems (cyclones) with the westerly winds. Cyclone tracks are determined by a semiannual oscillation, which consists of a contraction and expansion of the circumpolar pressure trough, more southerly in March and September and more northerly in January and July. Sea-level pressures indicate that this oscillation has decreased since the 1970s. Southerly tracking cyclones tend to drift into the edge of the polar cell region, balancing the heat loss from negative net radiation on the elevated ice sheet. As one element of the three-cell structure of the global atmospheric meridional circulation, the southern polar cell is roughly located over the Antarctic continent. Along the coastline, katabatic (gravity) winds carrying cold surface air down from the Antarctic plateau interact with the low-pressure systems, initiating gale-force winds that drive sea-ice formation, sea-ice advection, and the maintenance of ice-free areas (polynyas). This simple picture of atmospheric circulation is strongly modified by the orography of the Antarctic continent, the ocean circulation, and the distribution of sea ice, which reduces the air–sea exchange of heat and moisture.

The annual mean near-surface air temperature in the Weddell Sea decreases southward from –4.3°C (South Orkney Islands) to –22.2°C (Coats Land) with monthly means (January and July) of +1°C and –10°C, and –8°C and –30°C, respectively, at these locations. Interannual variability and trends in near-surface air temperature decrease from north to south, although the significance of trends is difficult to determine because of the relatively short lengths of the time series. A 90-year (1904–1994) record from the South Orkneys reveals a temperature increase of 2°C, while a 40-year (1957–1997) record from Halley Station in the southeastern Weddell Sea shows a slight temperature decrease. It is not yet known whether climatic changes observed in the northwestern Weddell Sea result from local factors or broader-scale circulation changes, but in the latter case there are no obvious links to the enhanced anthropogenic emission of greenhouse gases. In addition to a strong seasonal cycle in all atmospheric properties, the Weddell Sea experiences interannual climate fluctuations characterized by anomalies in sea-level pressure, sea-surface temperature, and sea-ice extent that appear to move around Antarctica at about the speed of the mean ocean flow. Studies of these periodic phenomena, sometimes referred to as the Antarctic Circumpolar Wave, Antarctic Dipole, or Southern Annular Mode, often suggest links to extrapolar variability such as the El Niño Southern Oscillation.

The ocean circulation in the Weddell Sea is dominated by the cyclonic (clockwise-rotating) Weddell Gyre, which displays a double-cell subsurface structure with centers on both sides of the Greenwich Meridian. The southern branch of the gyre is part of the coastal or slope front currents, the latter near the continental shelf break and separating cold shelf waters (~–1.85°C) from warmer open ocean waters (0.5°C–0.7°C). The northern branch of the gyre is guided by the topography of the South Scotia and Mid-Ocean Ridge, and interacts with the southern edge of the Antarctic Circumpolar Current. Southward recirculation at the eastern end of the gyre is poorly defined but may lie near 20° E at the surface and 80° E at depth, where the Kerguelen Plateau is a natural eastern barrier for dense water masses newly formed in the Weddell Sea. The transport of the Weddell Gyre, from *in situ* observations and numerical model studies, is estimated to be ~50 million $m^2\ s^{-1}$, with an interannual variability of ~15%. On the broad southern continental shelf, additional cyclonic circulation cells centered over the Filchner and Ronne Troughs transport ten times less water. Those cells interact with a separate circulation beneath the Filchner-Ronne Ice Shelf, driven by thermohaline (density) differences between water masses on the continental shelf and within the deeper sub-ice shelf cavity.

The Weddell Sea is known for its severe sea-ice conditions, always a threat to the ships that penetrate into this remote region, from *Deutschland* and *Endurance* to *Magdalena Oldendorff,* forced to spend the 2002 austral winter in a sheltered bay near the Greenwich Meridian. Sea ice can be considered a thin blanket between ocean and atmosphere, one that both controls and is controlled by the fluxes of heat, moisture, and momentum across the interface. Sea-ice extent, concentration, and thickness are determined by growth/decay and drift of the ice cover, in turn linked to dynamic and thermodynamic processes in the ocean, ice, and atmosphere. Intensive atmospheric cooling of the ocean surface below the freezing temperature (~–1.9°C on the southern Weddell Sea continental shelf) initiates the formation of sea ice, which then drifts northward and melts near the fringes of the Weddell Sea. The sea-ice cover experiences large seasonal changes, increasing from ~1.5 million km^2 in February to ~7.5 million km^2 in July, when it extends to ~55° S. Due to its annual renewal, the average sea-ice thickness is only ~0.8 m, much less than in the Arctic Ocean. However, extremes range from >3 m for the multiyear ice that survives the summer melt, predominantly in the western sector, to a few centimeters in leads and coastal polynyas.

Polynyas and leads are open water areas in the sea ice field, maintained by tidal action and divergent winds. Near the coastline these often narrow regions are the sites of the strongest sea-ice formation, with rates up to 0.1 m/day (equivalent to 17 m/yr). A much larger polynya appeared in the mid-1970s in the eastern Weddell, covering an area of $\sim$0.25 million km^2 in successive winters. This region near Maud Rise is known for the sporadic occurrence of smaller polynyas or thinner sea ice and is the initial area for the disintegration of the winter sea-ice cover. Large polynyas over the deep ocean may result from a complex interplay between ocean currents and bottom topography, tidal action, and unusual atmospheric forcing. In contrast to coastal polynyas, where the oceanic heat loss to the atmosphere is mostly balanced by the latent heat of fusion of ice, deep-ocean polynyas gain heat by the upwelling of warmer deep water. Under some atmospheric conditions the upper ocean heat flux may exceed 100 Wm^{-2}, while the flux is as low as 3 Wm^{-2} beneath the perennial sea ice. The average ocean heat flux in winter for the entire Weddell Sea is less than 40 Wm^{-2}.

In a deep ocean polynya, densification of the surface layer due to extreme heat loss can initiate convection and cooling to depths of 4000 m. This has consequences well beyond the Weddell Sea (e.g., a colder bottom layer in the Argentine Basin in the late 1980s has been related to the cooling of the deep Weddell Sea during the polynya years of the mid-1970s). However, processes on and near the Weddell Sea continental shelf are generally believed to have larger influences on deep Southern Ocean properties, and ventilation of the abyssal world ocean. New bottom water that is formed in the Weddell Sea corresponds to 25%–60% of the total production of dense bottom water in the Southern Ocean. Outside the Weddell Sea this water mass has historically been referred to as Antarctic Bottom Water and is carried as far as 40° N in the North Atlantic by the global thermohaline circulation. Some of this water may have first been advected into the Weddell Sea from the Indian sector sources off Prydz Bay and Enderby Land. It transports natural and anthropogenic substances from the ocean surface into the deepest layers of the ocean, where they are effectively stored for centuries.

The growth rate of sea ice determines how much brine is expelled to the ocean, increasing its density and causing deep convection. Some of the resulting dense shelf water moves toward the continental shelf break, where it mixes with different open-ocean components of circumpolar origin, ventilating the deep water and forming new bottom water. Some of the salty shelf water also flows into the deep Filchner-Ronne cavity, where its temperature exceeds the *in situ* melting point. This water melts the deep ice-shelf base, acquiring distinctive oxygen-isotope and noble-gas signatures in the process, rising as a plume of Ice Shelf Water with temperatures below sea-surface freezing point. Where Ice Shelf Water exits the cavity and reaches the continental shelf break, mixing with open-ocean components again results in the formation of new bottom water. The sub-ice shelf circulation is subject to seasonal variations, and may be sensitive to climate shifts and related changes in the sea-ice cover, with consequences for ice shelf mass balance. The export of sub-ice melt water affects the vertical stability of the shelf water with consequences for deep convection and sea-ice thickness. The total sub-ice shelf freshwater flux in to the Weddell Sea has been modelled at $\sim$10 thousand $m^2\ s^{-1}$, slightly more than net precipitation, but most precipitation falls in winter as snow transported off the continental shelf on top of the sea ice. For comparison, iceberg calving results in a slightly higher freshwater flux but mainly affects the surface waters of the circumpolar current (i.e., remote from the continent).

Despite its hostile environment, the Weddell Sea is home to a variety of marine animals, including whales, seals, and penguins, even during the austral winter. Their survival depends on the existence of fish, squid, and (especially) krill *(euphausia superba)*, a pivotal organism in the Antarctic food web with a total biomass estimated to exceed the earth's human population. Gigantic krill swarms appear in the northwestern Weddell Sea along the South Scotia Ridge where cold, oxygen-rich waters meet relatively warm, nutrient-rich waters of circumpolar origin, supporting phytoplankton growth. This region coincides with the abundance of large colonies of marine animals on the adjacent islands. Additional feeding grounds exist around Maud Rise and the sill of the Filchner Trough, where relatively warm, nutrient-rich water is displaced upward by the bottom topography. The abundance of krill is also keyed to the presence of sea ice, from the base of which their feeding apparatus can scrape sea-ice algae. The irregular shape of the sea-ice base provides hiding places for the juveniles, from predators like fish, penguins, and seals. The movements of those predators, which can now be tracked with sophisticated, satellite-supported instrumentation, provide information about the temporal and spatial variability of biological production, along with oceanographic and sea-ice conditions. Elephant seals fitted with satellite-linked position recorders on the South Shetland Islands migrated more than 1000 km through the winter pack of the western

Weddell Sea to the northern Filchner Trough, against the flow of the coastal current. Their choice of this track may well be related to the strong current shear that crushes the pack ice, creating breathing holes. This example illustrates the complex interplay of processes in the polar environment, and the importance of interdisciplinary studies.

HARTMUT HELLMER

See also **Antarctic Bottom Water; Antarctic Surface Waters; Circumpolar Current, Antarctic; Coastal Ocean Currents; Continental Shelves and Slopes; East Antarctic Continental Margin, Oceanography of; Filchner-Ronne Ice Shelf; Ice Shelves; Islands of the Scotia Ridge, Geology of; Larsen Ice Shelf; Polynyas and Leads in the Southern Ocean; Southern Ocean: Climate Change and Variability; Southern Ocean: Vertical Structure;Thermohaline and Wind-Driven Circulation in the Southern Ocean; Weddell, Ross, and Other Polar Gyres**

WEDDELL SEA REGION, PLATE TECTONIC EVOLUTION OF

Looking at the shape of present-day Earth it is difficult to imagine that the current distribution of the continents is just a snapshot of the crust's ongoing evolution. Earthquakes and volcanic eruptions, however, provide indications that the earth is still an active planet with moving continents.

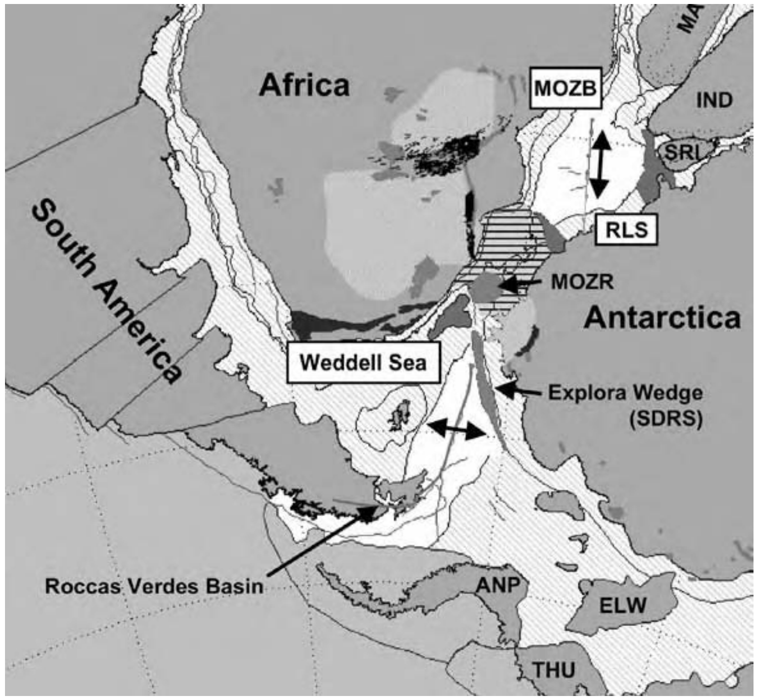
During Alfred Wegener's time (1826–1909), his theory of continental drift was hard for many scientists to believe. Today, we can measure the movements of the continents with high-precision GPS receivers and magnetic sensors. In order to look back in time at the history of continental drift, one has to investigate the magnetic field of the oceanic crust beneath the ocean basins. Here, information on the velocities and directions of the drift paths is stored in the differing magnetisation of the basaltic rocks in the oceanic crust, which results from numerous reversals of the earth's magnetic field during the past 200 Ma.

Marine and airborne magnetic investigations were carried out in the last 4 decades in order to unravel the drift history of the remote Antarctic continent. Combined with all the results from the world's oceans, these data provided a surprising image of the positions of the Southern Hemisphere continents at some 180 Ma. At that time, a large continent, Gondwana, existed in the Southern Hemisphere. South America, Africa, Madagascar, India, Australia, New Zealand, and, as its core, Antarctica, formed a huge land mass covered by widely varying landscapes, including forests. This general picture of the distribution of the continents, proven by magnetic measurements, has been quite well known for more than 3 decades.

Such huge land masses seem, for some reason, not to be stable configurations. At around 160 Ma, Gondwana started to separate step by step into the continental fragments that are known so well today. Although this general model has long been widely accepted, the details of the dispersal of South America, Africa, and India/Madagascar from Antarctica have ever since been the subject of controversy within the scientific community. One of the sources of this controversy is the pack ice around Antarctica, which prevented the investigation of critical parts of the ocean floor (e.g., the Weddell Sea). Special ice-strengthened research vessels are needed to operate in such "hostile" environments. Thus, most models were based on the combination of the sparsely distributed magnetic measurements and the onshore geology of the surrounding continents. Numerous strongly different geodynamic models existed that tried to describe the detailed separation of the southern continents. By the mid-1990s, one of these models proposed that the separation of Gondwana started in the western Weddell Sea at around 180 Ma. The more easterly basins of the Southern Ocean, like the Lazarev and Riiser-Larsen seas, are younger than 160 million years old and thus opened after the western Weddell Sea. In addition to this, the movements of microplates or small continents, and the presence of an extinct subduction zone in the western Weddell Sea, were proposed.

A renewed effort to close these gaps in knowledge started at the end of the 1990s with combined airborne and marine magnetic surveys in the Weddell, Lazarev, and Riiser-Larsen seas, in order to better constrain the early geodynamic evolution of the southern Atlantic and Indian oceans. The results of these detailed surveys were mostly surprising and significantly changed our view of Gondwana breakup.

The key problem in all older magnetic surveys of the South American (50°–08° W) to Indian (40°–70° E) sectors of the Southern Ocean was that the magnetic anomalies could not reliably be dated. A systematic pattern of aeromagnetic survey lines off the German base Neumayer, with a line spacing of 10 km, changed this situation. Clear magnetic lineations could be identified in the South American sector, and linked by a specific marine survey to a magnetic anomaly further north that dates unequivocally to 83 Ma. The oldest anomaly off Neumayer base could thus be dated to about 140 Ma. No clear magnetic anomalies were found in the Lazarev Sea, the western part of the African sector (10° W–40° E). A textbook example of magnetic lineations appeared



The configuration of the southern continents around 145 Ma. The oldest anomalies (thin lines) in the Weddell Sea (WS) and the Riiser Larsen Sea (RLS) are shown. According to the current knowledge in the Lazarew Sea, no spreading was active at this time. The hatched area west of Astrid Ridge indicates the location of a shallow sea or a still subaerial region (Jokat et al. 2003). However, the true sea floor spreading history for the Lazarew Sea is still under investigation. The interpretation shown here might change, if more details on the spreading history of the Mozambique Ridge is known. ANP: Antarctic Peninsula, ELW: Ellsworth-Whitmore Mountains, IND: India, MA: Madagascar, MOZB: Mozambique Basin, MOZR: Mozambique Ridge, RLS: Riiser-Larsen Sea, SDRS: Seaward dipping reflector sequences, SRI: Sri Lanka, THU: Thurston Island. Yellow: areas of old cratons, Red: volcanic material erupted before or during breakup.

again in the next basin to the east, the Riiser-Larsen Sea, the eastern part of the African sector. Here, magnetic anomalies dating back to 155 Ma were identified. These dates show that the opening of the ocean basins and, consequently, the dispersal of Gondwana was not as simple as previously thought; each ocean basin had a quite different history.

This new conceptual model for the region differs considerably in space and time from previous knowledge. In detail:

(1) The first deep-ocean basin to form as a consequence of Gondwana breakup was the Riiser-Larsen Sea, at around 160 Ma, and not the western Weddell Sea.
(2) The western Weddell Sea opened at around 147 Ma, much later than the previous prediction of 180–160 Ma.

As a consequence, these two basins were isolated from each other during their youth, and Africa was still connected to Antarctica in the region of the Lazarev Sea. This scenario is supported by rock samples drilled by the Ocean Drilling Program off Neumayer Base in 1987. Here, black shales were found at 500 m below sea floor, containing fossil fauna that point to an anoxic (oxygen-poor) shallow water environment. The age of the black shales ranges between 138 and 124 Ma.

(3) The detailed magnetic data off Neumayer base show that the young Weddell Sea opened by propagation towards the east.
(4) Finally, at some time between 140 and 135 Ma, Africa split from Antarctica and the Lazarev Sea started to form. Only since that time can a continuous ocean basin have existed from the Antarctic Peninsula to India, which was still attached to Antarctica. The southern polar ocean was born.
(5) All three continents, South America, Africa, and Antarctica, moved away from each other from the beginning of Gondwana breakup. At least 30 Ma of divergent stress finally resulted in the formation of new oceanic crust in the South Atlantic along the coasts of South Africa and Argentina from approximately 140 Ma on.

This prediction opposes all other models, which mainly deal with the South Atlantic independently.

(6) The extensive volcanism in South Africa and Antarctica dating from 183 Ma is not directly related to the formation of new oceanic crust. This strong magmatic activity is rather a precursor to the breakup event that took place 30 Ma later.

(7) The smooth and consistent northward movement of the South American plate in the Weddell Sea is in strong contrast to models that propose the movement of microplates, like the Ellsworth-Whitmore Mountains, in this region. In our current model, there is simply no room for such movements, and no geophysical information exists to support such a scenario.

Finally, it is worthwhile to note that the current model for the Gondwana breakup is consistent with all available geophysical data and most accepted geological interpretations. Despite the remaining problems, the new large magnetic data base provides strong constraints for the model. Research on this issue is ongoing, will further refine the model, and eventually will provide a better understanding on the deeper driving forces of supercontinent breakup.

WILFRIED JOKAT

See also **Geological Evolution and Structure of Antarctica; Gondwana; Plate Tectonics; Volcanoes**

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WEDDELL SEAL

The Weddell seal (*Leptonychotes weddelli,* a member of the true seals, family Phocidae) is one of the largest of all seals, weighing 350–500 kg. Despite its large, rotund appearance, it has an exceptionally small head, characterized by a relatively short muzzle, and disproportionately large brown eyes. On each side of the muzzle there are mobile mystacial vibrissae (used in feeding); on the back of the muzzle are rhinal vibrissae (surfacing), and above each eye there are 5–7 supraorbital vibrissae. The supraorbital vibrissae may help seals squeeze their bodies into tight spaces (e.g., ice holes) without getting stuck. They have short (10 mm), thick fur that is mottled with large darker and lighter patches and dorso-ventrally shaded blue-black on the back grading to silver-white on the belly. At birth, pups have a lanugo of grey-brown hair that they molt 9–21 days postpartum. Adults molt from January through to March. Following pupping, molt is delayed until after that of males and other females.

Weddell seals breed on the fast ice surrounding the shores of Antarctica and are circumpolar in distribution. No other mammal breeds as far south. They are most abundant in the fast ice with breeding concentrations occurring at sites where major perennial (i.e., predictable) tide cracks form in the ice. The seals haul out on the ice surface adjacent to these cracks, and also at tidal cracks that form along the shoreline. Weddell seals maintain access to the surface throughout the winter by reaming the ice with their teeth, which keeps breathing holes open.

Weddell seals are also found in the pack ice, particularly outside of the breeding season. The fast ice is the normal breeding habitat, but there are a few small breeding populations on some of the sub-Antarctic islands. One notable colony of about one hundred seals exists at Larsen Harbour, South Georgia (55° S).

The total world population has been estimated at between 750,000 and 1 million, with major concentrations in the Weddell and Ross seas. The most intensively studied population of Weddell seals is at McMurdo Sound (77° S) in the southern Ross Sea.

Female Weddell seals show variable movements outside the breeding season. Satellite telemetry of females in the Ross Sea has shown that some females are relatively sedentary, not straying from their summer colonies, but most females from the eastern part of McMurdo Sound spend the winter in the middle and northern parts of the sound before the annual shore-fast ice has formed in those areas, or in the pack ice up to 50 km north of the sound. The most far-ranging seals may swim long distances, up to 1500 km, moving extensively across the western Ross Sea. Weaned pups from McMurdo Sound leave their natal area by the end of February and travel north along the Antarctic coastline but remain within the Ross Sea region.

The marine habitat of Weddell seals is relatively well known compared to most other species of Antarctic seal. In McMurdo Sound, seals use all parts of this deep fjord (maximum depth >850 m). Weddell seals are renowned for being deep divers, and in McMurdo Sound they usually dive between 100 and 350 m. They have been recorded diving to at least 760 m. Female Weddell seals appear to use the entire water column for feeding, with very little time spent at the bottom, although the types of prey captured suggest that most feeding occurs in the middle of the water column and near the bottom.

Pupping begins earlier in the year at lower latitudes; with the first pups born in late August at Signy Island, South Orkney Islands (60°43′ S) and at South Georgia (55° S). At their farthest south in McMurdo Sound (77° S), pregnant females do not arrive at breeding areas until early October and they give birth to a single pup in October or early November. Mothers stay with their pups on the sea ice for about the first 12 days and from then until the end of lactation (at about 45 days) spend increasing amounts of time in the water. As in other phocid seals, there is a postlactation estrous.

The mating system is one of slight to moderate polygyny with the most successful males mating with three to four females within any one season. Male territories are probably set up early in the breeding season, and male vocalizations that are thought to function as a breeding display are most common in October and November. Spermatogenesis is initiated in August and viable sperm are produced from October through December. Weddell seals mate under the ice during late November and throughout December. By January males become azoospermic. Males first show spermatogenesis at three years, but these males are still physically immature and will not attend breeding colonies until they reach 5–7 years of age. Successful males are generally older than 7 years and have been found holding territories at breeding colonies up to at least 13 years of age.

In McMurdo Sound, the average age of first reproduction is 6 (range 2–11) years, but further north the age of first reproduction is delayed, with the average age at Signy Island being 7 years and at the Vestfold Hills (68° S) 8 years. The annual reproductive rate is approximately 0.68, varying between 0.55 and 0.75. This variation occurs in a predictable 4- to 5-year cycle and may be correlated with the Antarctic Circumpolar Current. Once they have commenced breeding females continue to reproduce throughout their life (18 years or longer), and there is no evidence of reproductive senescence. Like many long-lived animals, it appears that experience counts. Pups have a higher chance of surviving if their mother is older or has had more pups in previous years.

Pups weigh 22–30 kg at birth and double their weight in the first 10 days as they feed on extremely high-fat (60%) milk. They are weaned at 6–7 weeks of age and at a weight of about 110 kg, which means that pups triple their weight during lactation. Pups enter the water from 2 weeks of age and start diving almost immediately. Over the first 3 months of life their skill at diving improves rapidly. The first dives by pups rarely exceed 20 m and 2 min, but by weaning they are diving to 50–70 m for 3–4 min and already capturing the notothenioid silverfish *Pleurogramma antarcticum;* by 12 weeks they regularly dive to 100 m for 5–6 min.

Preweaning mortality is low in Weddell seals, with a mean of 13% but varies significantly with the age of the mother. Survival from 0–1 years is on average 42.9%, from 1–2 years 63.5%, and from 2–6 years 80.6 %, which is comparable to adults. Juvenile survival overall (0–6 years inclusive) is lower for males at 9.3% than for females at 14.2% and is also a function of the mother's age and experience, as mothers aged 10 years and older are much more likely to successfully wean their pup. The minimum adult male (5 years and older) survival rate of Weddell seals in McMurdo Sound is 76.2%, with the oldest male surviving to 22 years. The survival rate of adult females is about 85% per annum but declines to 74% from 10 years and older. The oldest females recorded have been 25 years of age.

Female Weddell seals in McMurdo Sound range from 187 to 265 cm, nose to tail length. The weight of mothers immediately after pupping is highly variable with 14 postpartum mothers weighing between 342 and 524 kg and an average of 447 ± 52 kg. Like most phocid seals, females principally use stored blubber reserves during lactation. However, as the lactation period is particularly long in Weddell seals, many females must actively hunt during lactation. Despite this additional feeding, the large amount of high-fat milk fed to the pup is very costly, and mothers lose up to 250 kg or 59% of their body weight during lactation at an average rate of 4.5 kgd^{-1}. As a result, nonbreeding females may be larger than breeding females.

There is no sexual dimorphism, and males range from 201 to 293 cm in length. Like females, males vary considerably in mass between years, presumably as a result of variation in food availability between years. Males lose weight over the course of the breeding season, although less than females. For example, at Razorback Island in McMurdo Sound in 1986, males weighed between 283 and 414 kg (mean = 365 kg) at the beginning of the breeding season. By the end of the season these same animals weighed 185–332 kg (mean = 273 kg) with a mass loss of 2–3 kgd^{-1}. In 1997–1999 at Turtle Rock (also in McMurdo Sound), males weighed 315–465 kg (mean = 393 kg) at the beginning of the breeding season and 294–429 kg at the end (mean = 348 kg).

The sex ratio of females to males at colonies varies from 2.8:1 to 8.9:1 during the course of a breeding season. Adult males establish underwater territories and defend them against other males, with territories changing in size over the course of the breeding season and displacements occurring after repeated challenges to established males. Males share breathing holes, but the volume of individual male territories may vary fivefold.

Weddell seals are the most vocal of all seals, with twenty-one to forty-four vocalization types. The number and type of vocalizations varies both with season and the location around the Antarctic continent. During the breeding season males call almost continuously when in the water, and males are the only animals to emit low-frequency (1- to 6-kHz) trills (in McMurdo Sound) or songs (in the Vestfold Hills Fjords). These male calls may act in territorial defense or as a form of display to attract females.

Weddell seals feed principally on fish and cephalopods, although they are also known to eat crustaceans. Krill have not been found in Weddell seal stomachs or scats. The predominant prey species, both by frequency of occurrence and by weight, in McMurdo Sound, at Davis Station, and in the Weddell Sea, is the Antarctic silverfish, *P. antarticum*. The Antarctic silverfish makes up more than 90% of the fish biomass in McMurdo Sound. Other important fish prey species include the pelagic nototheniids *Pagothenia borchgrevinki* and benthic *Trematomus* spp. Weddell seals are renowned for hunting large Antarctic cod *Dissostichus mawsoni*. Weddell seals approach large prey from below, and they have also been observed blowing air bubbles to flush *P. borchvgrevinki* out of the platelet ice immediately below the fast ice. Yearling Weddell seals in McMurdo Sound show different foraging strategies according to their size. Larger yearlings make long, shallow dives and appear to forage on benthic species such as *Trematomus* spp., whilst smaller yearlings forage in the water column on similar prey species to adults'. Weddell seals have on occasion been observed killing and eating penguins including gentoos and chinstraps.

Adult Weddell seals suffer little from predation because they are relatively inaccessible in the regions of fast ice and heavy pack ice. However, some Weddell seals, especially younger seals, are preyed upon by killer whales and to a lesser extent by leopard seals, particularly in the spring and summer when the ice breaks up.

Weddell seals were mainly protected from commercial hunting by their inaccessibility. However, near research stations, seals were killed to provide food for sled dogs, until dogs were banned under the Madrid Protocol, with the last dogs removed from Rothera Station in February 1994. All killing of seals in the Antarctic region is regulated by the Convention for the Conservation of Antarctic Seals (CCAS) and the Antarctic Treaty.

There is a single isolated population at White Island (78° S), which is cut off from the main McMurdo Sound population by an 18-km-wide unbroken ice shelf that is 10–100 m thick. The thirty-odd seals in this population produce three to five pups per year and have a higher rate of neonatal and preparturient mortality than in the main McMurdo Sound population. The pups also often have congenital deformities, which may indicate a degree of inbreeding. White Island animals are larger than elsewhere, with females weighing up to 686 kg and males up to 554 kg.

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See also **Antarctic Treaty System; Chinstrap Penguin; Circumpolar Current, Antarctic; Convention on the Conservation of Antarctic Seals (CCAS); Crabeater Seal; Diving—Marine Mammals; Fish: Overview; Gentoo Penguin; Leopard Seal; Ross Seal; Sealing, History of; Seals: Overview; South Georgia; South Orkney Islands; Zooplankton and Krill**

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WEST ANTARCTIC RIFT SYSTEM

The West Antarctic rift system encompasses all of West Antarctica except the Antarctic Peninsula. Topographically, it is dominated by a sub-sea-level trough that extends 3000 km from the Ross Sea, through the interior of West Antarctica to the Bellingshausen Sea. It is bounded along most of its length by the Transantarctic Mountains (TAM) and Ellsworth Mountains, which rise abruptly from –500 to –1000 m depths along the trough to summits of 4000–5140 m. This view of the rift system is deceptive, however. In addition to topography, the rift is defined by attenuated continental crust, block faulting, and alkaline volcanism. These features occur throughout coastal Marie Byrd Land (MBL) and Ellsworth Land. They indicate that the rift extends across the sub-sea-level trough to the coast, with no evidence for a northern boundary of unextended crust. It is thus highly asymmetrical, in contrast to many other rift systems. The MBL coastal highland is a volcano-tectonic dome that has risen within the rift system in late Cenozoic time, as described below. Early descriptions of the rift focused largely on the sub-sea-level trough and did not recognize the nature of the dome (Behrendt et al. 1991; LeMasurier 1978, 1990; Tessensohn and Wörner 1991).

Topographic Expression of Rifting

The earliest definitions of continental rifts were based on the distinctive topography of the "rift valley," or "graben," of East Africa (Gregory 1896; Seuss 1891), long before the tectonic significance of these features was understood. The West Antarctic rift is fully as large as those in East Africa, or the Basin and Range, but is unusual in the extensive sub-sea-level elevation of the main trough and the great depths of smaller ice-filled basins.

A north–south and east–west grain is expressed by the orientations of smaller basins within the trough. In the interior of MBL the Bentley subglacial trench and Byrd subglacial basin reach maximum depths of –2555 and –2000 m, respectively, and are oriented east–west. A narrow basin 250 km south of the Flood Range is more than 1500 m deep, and oriented north–south, and a trough of similar dimensions between the Crary Mountains and Mount Takahe is oriented west-northwest–east-southeast. The Ross Sea is underlain by three comparatively shallow (<1000 m) asymmetric basins, separated by rises (<500 m), all oriented roughly north–south. The thickness of the basin fill provides another perspective on these depths. The Byrd subglacial basin has only 0.5 km of sedimentary fill, whereas the Victoria Land basin, in the western Ross Sea, is filled with up to 14 km of late Mesozoic and younger strata (Cooper et al. 1991a).

Crustal Structure

During the International Geophysical Year (1957–1958), gravity surveys across West Antarctica revealed the large sub-sea-level trough, determined that it was underlain by continental crust ~30 km thick, and discovered the abrupt transition across the TAM front to crustal thicknesses of ~40 km (Bentley et al. 1960). Recent studies have largely confirmed these findings. Ritzwoller et al. (2001) found an average crustal thickness of ~27 km for the rift system, compared to ~40 km for East Antarctica. They show an area of low seismic wave velocities (reflecting high upper-mantle temperatures) that neatly defines the full area of the rift system from the Ross Sea to the Bellingshausen Sea, and from the TAM to the coast. They also show a well-defined asthenosphere (incipiently molten upper mantle layer) between ~55- and ~200-km depths, throughout the rift system. By contrast, seismic velocities in the Weddell Sea basin are significantly faster (cooler mantle), suggesting that this region is not now a part of the rift system. The Weddell Sea is underlain by oceanic crust that formed between ~155 and ~130 Ma (König and Jokat 2003).

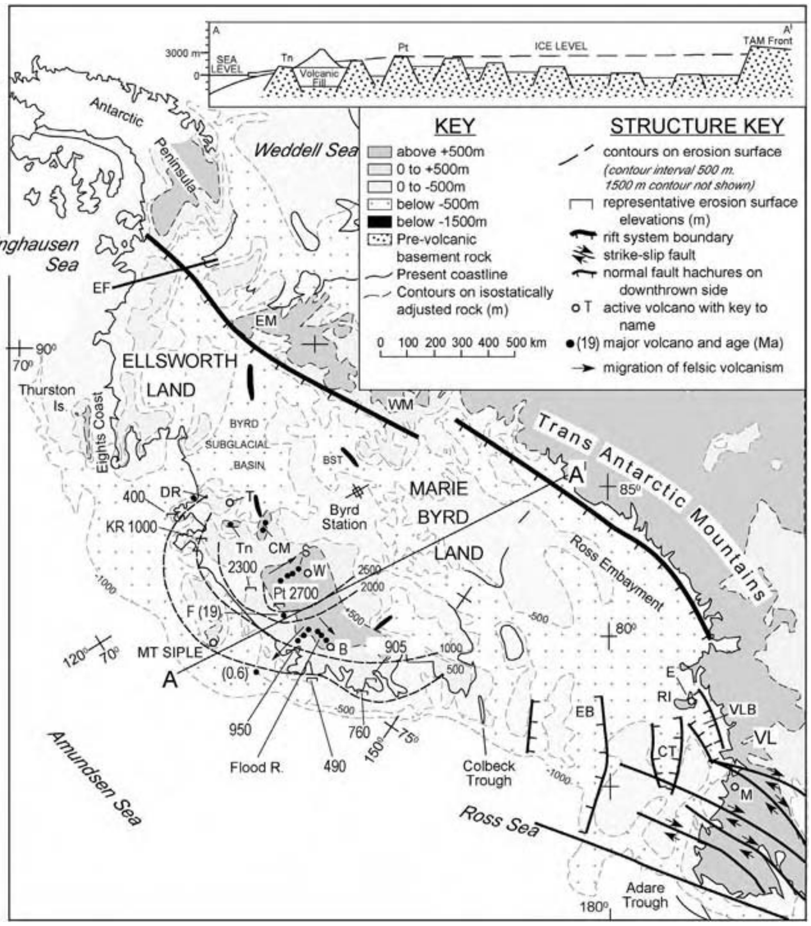
Winberry and Anandakrishnan (2004) found thicknesses of 21–31 km for the entire rift system, and only 34 km for East Antarctica. Their data also show a 21-km crust beneath the Bentley subglacial trench, a 25-km crust beneath the MBL dome, and faster mantle velocities in the rift interior compared to the dome region. Their crustal thickness beneath the dome is significantly less than previous estimates, implying that dome uplift is supported by low-density mantle. The thickness beneath the Bentley trench is one of the thinnest ever reported for the rift system, similar to estimates of ~20 km beneath the Ross Sea (Behrendt et al. 1991) and 19–23 km under the Victoria Land Basin (Cooper et al. 1991b).

The crust of West Antarctica is a collage of four continental blocks: the MBL, Thurston Island–Eights Coast, Ellsworth Mountains–Whitmore Mountains, and Antarctic Peninsula blocks. Each is characterized by somewhat different geologic assemblages and/or paleomagnetic pole positions, and each is separated from the other by deep subglacial troughs (Dalziel and Elliot 1982). Paleomagnetic data indicate that they moved relative to each other and to East Antarctica during the breakup of Gondwana in Mesozoic time (Grunow et al. 1987; Luyendyk et al. 1996). A conspicuous example is the 90° clockwise rotation of the Ellsworth Mountains, which was completed in early to mid-Cretaceous time (Grunow et al. 1987). Only two of these blocks, MBL and Thurston Island–Eights Coast, lie within the rift system, and the others lie on its flank. They do not define the rift in any sense but are simply components of crustal architecture.

Tectonic Structures

Ross Sea Sector

This is the "Ross Sea rift," as originally defined by Tessensohn and Wörner (1991). It is interesting to



Topography and structure of the West Antarctic rift system. Ice-free, isostatically adjusted bedrock topography is simplified from Drewry (1983). MBL dome structure is from LeMasurier (2005) and LeMasurier and Landis (1996). Victoria Land faults are simplified from Salvini et al. (1997). Ross Sea basins are simplified from Cooper, Davey, and Hinz (1991). The rift boundary between Ross Island and Adare trough has been omitted, to avoid clutter. B: Mount Berlin, BST: Bentley Subglacial Trench, CT: Central Trough, CM: Crary Mountains, DR: Dorrell Rock, E: Mount Erebus, EB: Eastern Basin, EF: Ellsworth Fault, EM: Ellsworth Mountains, F: Mount Flint, M: Mount Melbourne, RI: Ross Island, S: Mount Sidley, T: Mount Takahe, Tn: Toney Mountain, VL: Victoria Land, VLB: Victoria Land Basin, W: Mount Waesche, WM: Whitmore Mountains.

compare this sector with MBL, for an impression of different tectonic environments within the rift. The major structural features in the Ross Sea basin are three large north–south-trending grabens. Some narrow, deep basins that feed into the Ross embayment from the TAM (Drewry 1983) are clearly extensions of glacial valleys, overdeepened by erosion. However, seismic work in the Ross Sea has shown conclusively that the Victoria Land basin, Central basin, and Eastern basin are fault-controlled, asymmetric grabens (Cooper et al. 1991a). In the eastern Ross Sea, other north- to northwest-trending grabens (e.g., the Colbeck trough) have been mapped by Luyendyk et al. (2001).

The TAM front, which forms most of the southern rift boundary, is the most conspicuous structure in the entire rift system. Along the western Ross Sea, the boundary is marked by a series of northwest–southeast-trending, right-lateral, strike-slip faults, which are oblique to the mountain front (Wilson 1995). These structures are apparently inherited from the accretion of Proterozoic terranes in early Paleozoic time (Kleinschmidt and Tessensohn 1987). Salvini et al. (1997) propose that they are linked northwestward to transform faults along the Southeast Indian Ocean ridge, and southeastward to the Ross Sea basins. They suggest that extension and subsidence of the basins was driven by displacements along these faults. On the other hand, Fitzgerald and Baldwin (1997) argue that the asymmetric form of the Ross Sea grabens implies they were formed by displacements along low angle detachment faults. This mechanism also implies ~100% extension. Mylonitic gneisses dredged from the Colbeck Trough provide evidence of extension and fault displacement, around 98–95 Ma, and strain fabric analysis of the mylonites suggests 85%–100% extension (Siddoway et al. 2004).

Marie Byrd Land–Ellsworth Land

Coastal MBL is a largely ice-covered highland that appears to have experienced nearly continuous uplift and volcanism since the Eocene. It began with intrusion of the Dorrel Rock gabbro around 34 Ma, and was quickly followed by uplift and erosion of 3+ km of overlying rock, mainly in Oligocene time (Rocchi et al., in review). Around 29–27 Ma, the focus of uplift shifted 600 km westward, where dome uplift coupled with volcanism began at Mount Petras. The MBL dome is defined by elevations of a very low relief erosion surface exposed in block faulted nunataks, where it bevels mid-Cretaceous and older rocks. The elevations of these blocks rise from 400–800 m along the coast, and to 2700 m at Mount Petras, defining a dome ~800 km across, with perhaps 3 km of structural relief (LeMasurier and Landis 1996). Eighteen felsic volcanoes are distributed across the dome, mainly in north–south and east–west chains that appear to be fault controlled. The oldest volcano (19 Ma) is at the dome crest, and the others become younger toward the flanks, where all the active volcanoes are found. This pattern and the systematic increase in age with elevation of basalts that rest on the erosion surface demonstrate a very close association between dome growth and volcanism. The two patterns together suggest that the dome has been rising since 27–29 Ma, at ~100 m/my (LeMasurier and Landis 1996; LeMasurier and Rex 1989).

Farther east, the Ellsworth fault forms the southern boundary of the Antarctic Peninsula block, near the eastern boundary of the rift system. Kellogg and Rowley (1991) suggest that this fault is an on-land continuation of the Tharp fracture zone, a part of the Pacific–Antarctic ridge and transform fault system, that was active from ~85–50 Ma (Barker 1982). Other more westerly, sea-floor fracture zones trend southward toward the MBL coast, suggesting that the north–south and east–west fault systems, and perhaps the interior basins in MBL, may have been controlled by them during the MBL–New Zealand breakup, between 90 and 79 Ma (Larter et al. 2002).

Rift Volcanism

The earliest rift-related igneous activity is recorded by a 48-Ma gabbro in northern Victoria Land (Tonarini et al. 1997) and the 34-Ma gabbro in MBL. Volcanism has continued episodically to the present day, where it is represented by continuous activity at Mount Erebus, and by evidence of late Pleistocene activity at Mount Melbourne (northern Victoria Land) and Mounts Takahe, Berlin, Siple, and Waesche in MBL (McIntosh and Wilch 1995; Wilch, McIntosh, and Dunbar 1999; Wörner and Viereck 1990).

The largest of the well-exposed volcanoes are Mount Erebus (3795 m) and Mount Siple (3110 m), each with an exposed volume of ~1800 km^3 and more than 3000 m of relief (LeMasurier 1990). For comparison, the largest volcano in the Cascade Range, Mount Shasta, has a volume of 350 km^3 (Christiansen 1990). The highest volcano is Mount Sidley (4181 m), but like most MBL volcanoes it is partly buried beneath the continental ice sheet, and its total volume cannot be estimated. There are eighteen of these large volcanoes in MBL and a similar number along the Ross Sea coast. Many are composed largely or entirely of felsic rock (a rock like phonolite or rhyolite, composed of abundant light-colored minerals [Jackson 1997]); others are mainly basalt with a felsic cap. Small (<1 km^3) volcanic cones are much more abundant. These are mostly basaltic, and are distributed throughout the western Ross embayment and MBL provinces and in small volcanic centers on the coast of Ellsworth Land (LeMasurier 1990). Although felsic rocks are conspicuous, because they occur in large volcanoes, they appear to be subordinate in volume to basalt. In MBL, felsic rocks are believed to represent 10%–30% of the volume of volcanic rock (LeMasurier et al. 2003). Aeromagnetic data over the interior of West Antarctica have been interpreted to represent subglacial volcanic fields with a volume exceeding 1 million km^3 (Behrendt et al. 1994). This interpretation is supported by Ritzwoller et al. (2001) but is not consistent with cooler mantle in the interior (Winberry and Anandakrishnan 2004) or with the scarcity of volcanic rock in West Antarctic ice stream cores (Vogel 2004).

The alkaline volcanoes of the rift system include examples of a distinctive rock type called "rhomb porphyry," or "kenyte," first described from the Oslo rift and East African rift, respectively, and recognized by the presence of large (~5-cm), elongate feldspar crystals with rhombic cross-sections. Alkaline rocks are so named because they are relatively rich in the alkali elements sodium and potassium. This is expressed mineralogically by abundant alkali feldspars and by the common presence of green and blue alkali pyroxenes and amphiboles, normally visible only under a microscope. These rocks are geochemically indistinguishable from those found in oceanic island volcanoes, but the volume of felsic rocks in the rift system is large compared to oceanic volcanoes. Felsic rocks throughout the rift show little or no evidence of crustal contamination. They are essentially mantle-derived rocks produced by fractional crystallization of basalt at various levels in the crust (Kyle, Moore, and Thirlwell 1992; LeMasurier et al. 2003). Volcanoes found elsewhere in the Pacific "rim of fire" originate above subduction zones and are consequently more contaminated by the crust, more water-rich, and more explosive than those in the West Antarctic rift.

Rift History and Evolution

Our understanding of the evolution of the West Antarctic rift system is sketchy because so much of it lies beneath thick ice cover. The following outline is an attempt to briefly list major events that have been more or less agreed upon.

(1) *Jurassic*. Schmidt and Rowley (1986) used the distribution of late-Jurassic flood basalts, erupted during the separation of India and Africa from East Antarctica, to define a Jurassic "Transantarctic rift system" that formed along the TAM, from the Ross Sea to the Weddell Sea. The extension into the Weddell Sea was progressively blocked off by rotation of the Ellsworth Mountains, resulting in the present extension into the Bellingshausen Sea, which probably dates from the early Cretaceous.

(2) *Mid-late Cretaceous extension.* The interval from ~110–80 Ma, prior to and during the breakup of New Zealand and West Antarctica, is believed to be the main period of extension and crustal thinning in the rift system (Lawver and Gahagan 1994). Evidence for prebreakup extension includes (1) 90- to 110-Ma mafic dikes in MBL that trend east–west, parallel to the continental margin (Storey et al. 1999), (2) exhumation and rapid cooling of mid-crustal rocks in MBL between 105 and 94 Ma (Richard et al. 1994), (3) 98- to 85-Ma Ross Sea mylonites noted above, and (4) structural and stratigraphic evidence of rifting in New Zealand, extending back to ~100 Ma (LeMasurier and Landis 1996, and references therein).

(3) *Late Cretaceous breakup and subsidence.* Breakup began ~90 Ma, and New Zealand separated from MBL during the interval 83.0–79.1 Ma (Larter et al. 2002). The West Antarctic erosion surface, and a contemporaneous surface in New Zealand, record prolonged late-Cretaceous tectonic stability and erosional leveling, which extended across West Antarctica and contiguous portions of prebreakup New Zealand. After breakup, this was followed by subsidence to the –500-m to –1000-m levels that characterize most of the rift system today (LeMasurier and Landis 1996).

(4) *Cenozoic Transantarctic Mountain uplift and Ross Sea subsidence.* Apatite fission track analyses provide evidence for TAM uplift in the Early and Late Cretaceous and early Cenozoic (~55 Ma), with about 5 km of uplift since early Cenozoic time (Fitzgerald 1992; Fitzgerald et al. 1986; Stump and Fitzgerald, 1992). Episodic subsidence and extension of Ross Sea basins appears to have accompanied mountain uplift (Cooper, Davey, and Hinz 1991), but the main phase of uplift began around 55–50 Ma (Fitzgerald and Baldwin 1997), more than 30 m.y. after the main phase of extension. Cenozoic extension has been reported along the axial part of the Victoria Land basin ("Terror rift"), beginning in the Eocene (Cooper, Davey, and Behrendt 1991). Cande et al. (2000) report evidence for ~180 km of east–west extension across the Adare trough between 43 and 26 Ma. The great depth of the MBL interior basins implies that the ice is itself part of the basin fill, and that some extension has taken place there since the development of the ice sheet, probably in the early Miocene (Bart 2003; LeMasurier and Rocchi 2005). This is consistent with evidence for "locally extreme extension" beneath the Bentley subglacial trench (Winberry and Anandakrishnan 2004).

(5) *Mid-Cenozoic to recent volcanism; growth of the MBL dome.* Igneous activity has accompanied TAM uplift and Ross Sea subsidence since 48 Ma along the southern boundary of the rift. Rocchi et al. (2002) propose that this was initiated by plate motions that opened the Adare trough ~43 Ma, reactivated the northwest–southeast fault system, and induced decompression melting in the sublithospheric mantle. In MBL, 2000 km to the east, there is as yet no evidence for a plate-tectonic mechanism that could produce persistent dome uplift and volcanism since Oligocene time. Mantle plume support of the MBL dome has been proposed by LeMasurier and Landis (1996). This is consistent with the high elevation and

thinner crust over the dome (Winberry and Anandakrishnan 2004), and with seismic tomographic images that show vertical low-velocity structures extending down to the mantle transition zone beneath the MBL volcanic province (Sieminski et al. 2003). It is also consistent with the stationary plate environment of Antarctica that volcanism and uplift have remained focused at one spot since ~27 Ma, rather than producing the more familiar unidirectional volcanic chains associated with moving plates.

Summary

The West Antarctic rift system is similar to others in its attenuated crust, alkaline volcanism, and extensional fault structures. It is unusual in its pronounced asymmetry, largely sub-sea-level elevations, and the predominance of oblique strike-slip faults, rather than range-parallel normal faults, along the Victoria Land mountain front. The asymmetry seems to be a result of prolonged mid-Cretaceous extension that separated the northern rift flank (New Zealand) from Antarctica, leaving an ocean basin in between. This is one of the least-studied rifts on Earth, and much is still to be learned. Among the most vexing problems are (1) the cause and mechanism of TAM uplift, (2) the amount and timing of extension, and (3) what lies beneath the ice sheet. The latter is perhaps the most intractable problem, but it conceals evidence that bears on the total volume of rift-related volcanic rock, and hence the thermal context of rift evolution, and it conceals sedimentary basin fill that could elucidate the timing and magnitude of extension.

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See also **Antarctic Peninsula, Geology of; Gondwana; International Geophysical Year; Mount Erebus; Transantarctic Mountains; Volcanoes**

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WHALES: OVERVIEW

Species Found in the Antarctic

The cetaceans, members of the order Cetacea (from the Latin "cetus," a large sea animal, and the Greek "ketos," a sea monster) are the most highly adapted of the aquatic mammals, spending their time exclusively in water. They comprise what are commonly known as whales, dolphins, and porpoises. However, the distinction between these is somewhat confused, with, for example, several members of the family Delphinidae having common names using the word "whale" (e.g., the killer whale, *Orcinus orca*) and some species generally known as "small cetaceans" that are larger than some known as "Great Whales" (e.g., Arnoux's beaked whale, *Berardius arnuxii*, is larger than the Antarctic minke whale, *Balaenoptera bonaerensis*).

This article focuses on the traditional Great Whales. Of the thirteen recognised species, eight spend a part of each year feeding in the Antarctic. All but one are members of the suborder *Mysticeti,* the baleen whales. There are six species of the family Balaenopteridae, the rorquals: the blue whale *(Balaenoptera musculus);* the fin whale *(B. physalus);* the sei whale *(B. borealis);* the Antarctic minke whale *(B. bonaerensis);* the dwarf form of the common minke whale *(B. acutorostrata);* and the humpback whale *(Megaptera novaeangliae)*. The blue whale comprises two subspecies, the "true" blue whale *(B. m. musculus)* and the pygmy blue whale *(B. m. brevicauda)*. There is also one member of the Balaenidae (*Eubaleana glacialis,* the southern right whale). The only member of the suborder Odontoceti or toothed cetaceans considered here is the sperm whale (family Physeteridae, *Physeter macrocephalus*). There are several populations of each of the species found in Antarctic waters.

Adaptations

Fossil whales go back to at least the Middle Eocene (c. 55 Ma). The most obvious adaptations from terrestrial mammals relate to changes in body shape as a result of their aquatic environment (e.g., streamlining). Power is provided by the large tail and horizontal flukes (fish tails operate in a vertical plane), whilst "steering" is provided by the flippers (adapted forelimbs); the rear limbs are vestigial. The skull has adapted in many ways, the most apparent being the presence of "blow holes" (paired in Mysticetes, single in Odontocetes) on top of the head. Whales have almost eliminated hair, and the skin is smooth (except where infested by parasites) and flexible to reduce resistance; the thermal function of hair is replaced by a thick layer of fatty tissue called "blubber." Bone structure has also been modified to improve buoyancy and take account of the denser aquatic environment. Other important adaptations include those related to diving (e.g., lung size, blood supply, and physiology).

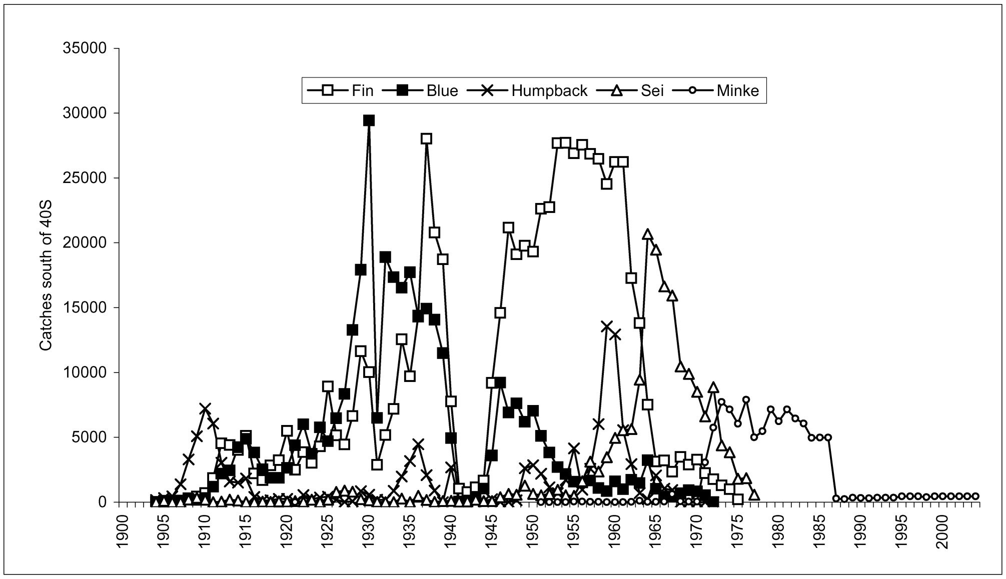
As noted above, baleen whales are called after their "baleen." They have several hundred elongated triangular baleen plates growing down on either side from their upper jaw. Although popularly called "whalebone," they are made of a horny material (keratin) and not bone. The baleen plates are 1–3 cm (1/2–1 inch) apart and fringed internally with fibres forming a sieve. The whale filters large mouthfuls of water containing the shrimps or other small crustaceans or fish on which it feeds. Female baleen whales are generally about 5% larger than males.

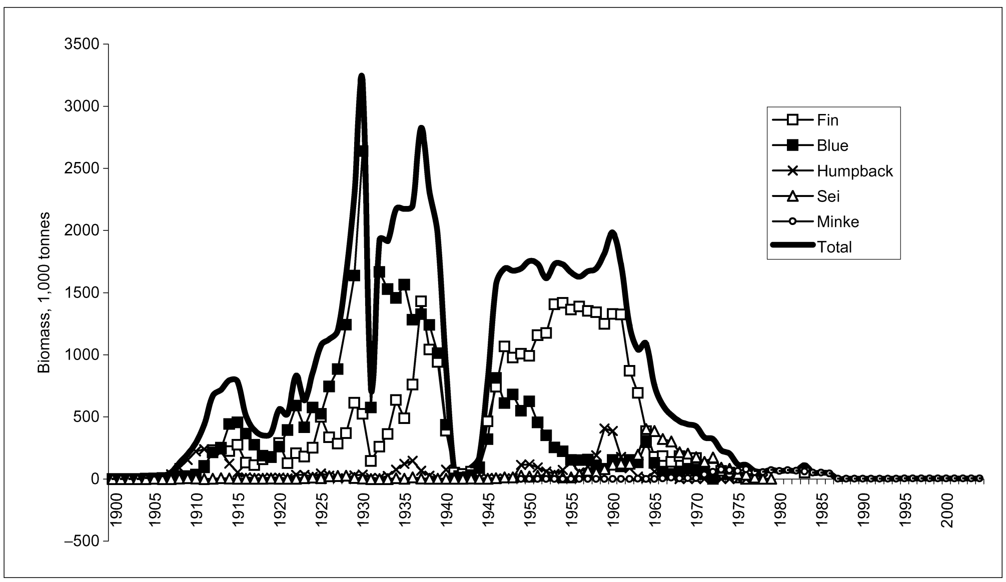
The rorquals (from the Norse for "grooves") are the most streamlined of the baleen whales. They are named after the grooves that run from the lower jaw to the abdomen, which allow the mouth to expand to dramatically increase the volume of water engulfed when feeding, whilst still allowing streamlined swimming when not feeding. The members of the genus *Balaenoptera* are the most streamlined and the most obvious difference between them is their size, ranging from the true blue whale (average 25–27 m) through the fin whale (average 21–22 m) and sei whale (average 15–16 m) to the Antarctic minke whale (average 10–11 m). The other rorqual, the humpback whale (average 13–14 m), is less streamlined and has much longer flippers. By contrast, the remaining Antarctic baleen whale, the southern right whale (average 14–15 m) has no grooves but a huge mouth framed by a bowed lower jaw. Consequently it is less streamlined and a much slower swimmer.

The sperm whale is easily recognised by its huge head (comprising about 1/3 of the body) containing the waxy spermaceti oil. This has been linked with both diving ability and sound production. Sperm whale males are considerably larger than females (c. 15–20 m versus 10–13 m).

Distribution and Migration

Whales are a migratory species, with baleen whales migrating between the summer feeding grounds in the





Top: Graph showing catches of the rorquals from 1904–2004 for the region south of 40° S. Bottom: Graph showing the approximate biomass removal for the rorquals that fed in the Antarctic from 1900–2004. It includes catches from throughout their range. Average weights for the species were assumed to remain constant throughout the time period (blue, 88 tonnes; fin, 50 tonnes; humpback, 27 tonnes; sei, 18.5 tonnes; minke, 9 tonnes).

Antarctic and the winter breeding grounds in tropical or semitropical waters (although the locations of the breeding grounds are only known for the humpback and southern right whales). Little or no feeding occurs outside the feeding grounds so the animals have to build up vast energy reserves (stored as blubber) during the feeding season. The sperm whale is somewhat different, with only older large males migrating to the Antarctic and no evidence that they do not feed at other times of the year.

In general, the whales found in the Antarctic spend only the austral summer there, taking advantage of the extremely high productivity at that time of the year, although there is increasing evidence (e.g., from acoustics) that some animals remain in the Antarctic much longer and may not migrate some years.

The timing of the migration into Antarctic waters differs somewhat by species. Whaling data suggest that blue whales reach the Antarctic before fin whales, with sei whales arriving last of all. Minke whales seem to spend the least time in the Antarctic, peaking in late December and leaving by late February. Humpback whales arrive about the same time as minke whales but leave later. Sperm whales peak between late December and mid-February. The length of time spent on the feeding grounds may be related to body size and reproductive condition. For baleen whales, there is also evidence of different reproductive classes migrating at different times. Pregnant females, for example, arrive earliest on the feeding grounds and leave latest, presumably to build up sufficient energy reserves for lactation.

There is also a general pattern of segregation of species, presumably related to prey availability and niche separation. For example, most true blue and minke whales are found in the high productivity waters near to the ice edge. Distribution of most fin and sei whales seems to be related to the Antarctic Convergence, with fin whales found between around 55°–62° S (i.e., just south of the convergence) and sei whales mainly on or near the convergence, although large adults can be found near the ice. Pygmy blue whales and dwarf minke whales tend to be found at similar latitudes to fin whales. Right whales and humpback whales have been found as far south as the ice edge, although they are thought to be more prevalent north of 55° and 60° S, respectively. Sperm whales are most commonly found south of around 64°–66° S.

Although all but pygmy blue whales have a circumpolar distribution, there is a general tendency for lower densities in the region between about 80° and 150° W. Sperm whale densities are highest from 90°–120° E and 150°–180° E.

Diet

The primary food source of all of the baleen whales (except the sei whale), and indeed many other species ranging from fish through birds to seals, is krill, *Euphausia superba,* a shrimp-like crustacean that is found throughout the Antarctic. Only very-high-density swarms of krill provide suitable food for whales, since the energetic costs of swimming through the water with an open mouth are high. This requirement will be reflected in the distribution of whales. In addition to some geographical segregation, different requirements for sizes of swarms may reduce competition between species found in the same areas, such as the smallest rorqual, the minke whale, and the largest, the blue whale, which are both found near to the ice edge. Sei whales feed on a wider range of species, including a different Euphausiid *(E. vallentini)* as well as copepods (e.g., *Calanus tonsus*) and amphipods (e.g., *Parathemisto gaudichaudii*).

In the Antarctic, sperm whales feed primarily on large squid, the main species being *Moroteuthis knipovitchi, Kondakovia longimana,* and *Mesonychoteuthis hamiltoni,* although other species including fish (e.g., *Ceratius holbolli* an angler fish) are eaten. Krill is the primary food of several squid species.

Life History and Social Structure

Whales are generally typical "K-selected" mammals, with low birth rates, slow growth, late maturation, and high survival rates.

Compared to odontocetes, baleen whales appear to have a relatively simple reproductive strategy and social structure, although little is known about the balaenopterids. There are no lasting male–female bonds, and males compete with each other for females. This can be either directly, as in humpback whales, where male fights can be quite violent, or indirectly, via sperm competition as in the southern right whales which have amongst the largest testes of any whales, species (the weight of both testes can exceed 900 kg, whereas the testes of the much larger blue whale weigh around 70 kg) or some combination of both. Humpback whales also exhibit "singing" behaviour to attract females. Large aggregations of feeding baleen whales can sometimes be seen in the Antarctic, although the degree of cohesion of these is unclear. Only for the humpback whale is there good evidence of cooperative feeding.

Gestation in the baleen whales is thought to be around 1 year. Almost exclusively, there is only one foetus, and there is no evidence of surviving twins. Neonates tend to be around 30% of the length of adults. There is some variation in calving rate by species, ranging from one per year in Antarctic minke whales to one every three years for southern right whales. The other rorquals generally have one calf every 2 years. The mother–calf bond is relatively short in baleen whales, with most weaned by the time they reach the feeding grounds (i.e., by about 4–7 months)—whale milk is extremely nutritious. The age at first calving is around 5–10 years. Longevity appears to be related to body size, with minke whales living to 50–60 years whilst fin and blue whales may reach up to 100 years.

Sperm whales have a much more complex matriarchal social structure. The basic social unit comprises 10–15 adult females and their young. Females give birth about once every 5 years and reach sexual maturity at about 9 years. These social groups remain in warm to temperate waters north of around 40° S. Males leave the family unit from about 5–15 years old, forming loose ''bachelor'' aggregations. The size of these aggregations decreases with age, the largest and oldest individuals usually being seen alone. It is the larger older animals that enter Antarctic waters. Only the large socially mature males (over about 25 years old) participate in mating, although they may spend only a few hours with the females. Teeth marks suggest considerable male–male competition.

The primary predator of whales is the killer whale *(Orcinus orca),* which is common in Antarctic waters (and indeed elsewhere) and has been known to attack both adults and calves of all species, even the blue whale. There have been some suggestions that killer whale predation may play an important role in Antarctic minke whale dynamics.

Status

The primary factor affecting the status of the whales that visit Antarctic waters has been whaling. The Antarctic was the scene of the heaviest modern whaling and several species were greatly reduced, despite the introduction of international regulations from 1946. However, whaling outside the Antarctic also had a major impact on some species. For example the southern right whale was severely reduced by whaling, largely on its breeding grounds, even before the advent of modern whaling. At least in terms of numbers, catches were relatively small in the Antarctic (over 3000 between 1951 and 1971 by illegal Soviet operations, compared to total Southern Hemisphere catches of up to 164,000 prior to 1920), although this would have been sufficient to impede recovery. The humpback whale was caught in both its feeding and its breeding grounds (again, in the latter case it had also been caught prior to modern whaling).

Antarctic whaling began in 1904 and expanded dramatically, particularly with the invention of the stern slipway, which allowed factory ships to operate in all Antarctic waters. The worst hit was the true blue whale, which was reduced to a tiny fraction of its original population size (although estimating preexploitation size is not easy), but the fin, sei, and humpback whales were also reduced to low levels. Only the Antarctic minke whale has been relatively unaffected by whaling operations.

The primary method for estimating abundance of cetaceans is by sightings surveys. These provide an estimate of a number of animals in a particular geographic area at a particular time. The International Whaling Commission has been conducting a series of sightings surveys in the Antarctic, mainly in waters south of 60° S, as they have been primarily directed at Antarctic minke whales. As the distribution of several of the species extends further north than this, the estimates for those species are only partial estimates. In addition, for certain species with appropriate natural markings (humpback, southern right, and sperm whales), estimates can be obtained from mark–recapture estimates based on photographs. Estimating abundance and trends for cetaceans is difficult, especially for such a vast area as the Antarctic. However, it is encouraging that for a number of species, there are signs that at least some populations are increasing.

Trophic Interactions

It seems inevitable that the exploitation of seals (especially crabeater seals, *Lobodon carcinophagus*) and whales must have had a major impact on the balance of the Antarctic ecosystem. It is questionable, even in the absence of human activity, whether the original balance can ever be restored. For example, if the unexploited population of blue whales in the Antarctic was around 200,000 and the present population is as many as 2000—then the reduction in blue whale biomass is some 16–20 million tonnes. Depending on a number of assumptions, this could amount to a reduction in krill consumption amounting to anything from 35 to 90 million tonnes of krill each year. Taking all marine mammal harvesting into account, estimates of as much as 55–165 million tonnes of ''surplus'' krill per year have been made for the exploited versus unexploited Antarctic, although such estimates are contingent on important and unverifiable assumptions.

The possible effects of this ''surplus'' are difficult to determine, and a number of different hypotheses have been proposed. From a baleen whale perspective, these include suggestions that there have been increases in Antarctic minke whales in response to the decline in blue whales that have inhibited the recovery of the latter. Others have suggested that it is unlikely that there is any interspecific competition at all between whales and that food has never been a limiting factor in whale dynamics in the Antarctic. To properly understand the true situation may never be possible. It will require sophisticated ecosystem modelling of all aspects of the past and present Antarctic. Even if appropriate models can be developed, it is

Crude Summary Information Relevant to Status of Some Whales Found in Antarctic Waters

Species	Approximate Total Catches (% S of 40° S)	"Original" Size	Present Abundance (and Year Applicable)	Evidence of Trend	Method	Area Covered
True Blue	358,000 (95%)	200,000–240,000	1700 (1996)	+2%–8%	Sightings	South of 60° S
Fin Whale	702,000 (97%)	200,000–400,000	5500 (1996)	Unknown; suggestions of increase in some areas	Sightings	Partial, south of 60° S
Sei Whale	203,000 (88%)	Unknown	Unknown	Unknown	n/a	
Antarctic Minke Whale	118,000 (88%)	Unknown	Analyses in progress; perhaps around 300,000	Unknown, but apparent decline Being investigated	Sightings	South of 60° S
Humpback Whale	164,000 (72%)	75,000–100,000	30,000 (recent)	+10% per year in Australia	Mark–recapture, sightings	Most areas, including outside Antarctic
Southern Right Whale	167,000 (2%)	60,000–100,000	7500 (1997)	+7%–8% per year	Mark–recapture	Primarily breeding areas off S. Africa, Argentina, and Australia
Sperm Whale	340,000 (63% since 1900)	Unknown	Unknown	Unknown	Mark–recapture	Only available for small local areas

There is considerable uncertainty in many of these estimates, especially of initial population sizes, which, where they exist, are based upon modelling exercises. Estimates of present abundance often have wide confidence intervals. The estimates are summed for the total circumpolar region and are not broken down by population, even where known. Catches are for the whole Southern Hemisphere, not just the Antarctic, and for the years 1904 to the present, except for southern right whales, the catch number of which includes figures from 1770.

questionable whether sufficient data exist or can be collected that will allow an unambiguous modelling exercise to occur, either in terms of explaining the past or predicting the future. Added to these difficulties are the potential effects of climate change and global warming on the Antarctic, and in particular krill and other krill predators. It is particularly important that efforts to monitor abundance be maintained or increased.

GREG P. DONOVAN

See also **Beaked Whales; Blue Whale; Cetaceans, Small: Overview; Diving—Marine Mammals; Fin Whale; Humpback Whale; International Whaling Commission (IWC); Killer Whale; Minke Whale (Antarctice Minke Whale); Sei Whale; Southern Right Whale; Whaling, History of**

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WHALING, HISTORY OF

Antarctic twentieth-century whaling was an industry very different from whaling in earlier times. It was "industrialized" and large-scale to a much greater extent than before. New whale species were chased on new whaling grounds. New whaling nations that had not taken part in world whaling before entered the business. On the other hand, the country that had completely dominated nineteenth-century whaling, the United States, almost disappeared from the industry. With New England as a base, the nineteenth-century industry had been global, with catching grounds in the Arctic, the North and South Atlantic, the Indian Ocean, and the North and South Pacific. It was only to a very limited extent that the American whalers ventured into Antarctic waters. Whales were chased around the sub-Antarctic islands, but the major catching grounds were farther north. Nineteenth-century economic exploitation of Antarctic resources was instead left to sealers. They were replaced by the new whaling industry in the early twentieth century.

The Antarctic Whaling Industry: Whales Killed 1909/1910–1979/1980

Year	Number of Whales killed
1909/1910	6099
1919/1920	5441
1929/1930	30,655
1939/1940	32,900
1949/1950	32,396
1959/1960	38,892
1969/1970	11,949
1979/1980	8074

Source: International Whaling Statistics.

The Exploratory Phase

Antarctic whaling had its origin in Norway, where so-called "modern" whaling was conceptualized in the 1860s by Svend Foyn. His system of whaling, using a powerful steam whale-catcher boat equipped with an explosive grenade harpoon gun, was distinctly different from old whaling, and made possible the catching of the large, fast swimming rorquals (blue whales, fin whales, humpback whales, and sei whales). The new industry grew in Norway towards the turn of the century. However, by the 1890s there were clear signs of depletion of the whale stocks, and the whalers started to look for new hunting grounds. This brought them to Iceland, Spitsbergen, and the Antarctic.

Both in Australia and in Scotland plans for whaling in Antarctic waters were discussed beginning in the 1870s. They were well known in Norway. In the early 1890s, four expeditions sailed south from Scotland and Norway in search of new whaling grounds. Two consecutive Norwegian expeditions with *Jason* became most important for the future development of the trade. They were initiated by the whaling and shipping owner Christen Christensen and captained by Carl A. Larsen. On the second trip, Larsen visited South Georgia and made his first plans for a whaling shore station there. His third Antarctic trip also was important. With the Swedish South Polar Expedition (1901–1904), he again visited South Georgia and saw Grytviken for the first time: a sheltered harbour that had earlier been used by American sealers. After the expedition, Larsen ended up in Buenos Aires, where he collected local support for the foundation of the first Antarctic whaling company, Compañia Argentina de Pesca. In 1904 Larsen and a group of Norwegian whalers arrived in Grytviken and set up a whaling shore station there.

The expeditions of the 1890s had been pursuing bowhead (southern right) whales. Larsen for the first time brought a small steam whale-catcher boat to southern waters to chase the rorquals, thus starting the era of modern whaling in Antarctica.

Early Antarctic Whaling Grounds

From the beginning in 1904, the industry expanded in two geographical areas, South Georgia and the South Shetland Islands. The industry was also from the beginning organised in two different ways: with a shore station or a floating factory ship as the base for the activity.

At South Georgia, many whalers followed in the wake of Larsen's establishment. In a matter of a few years, six whaling stations had been erected: Grytviken, Husvik Harbour, Stromness Harbour, Leith Harbour, Ocean Harbour, and Prince Olav Harbour. The companies were of several nationalities, but a majority of the whalers were recruited in Norway.

The year after Larsen established himself at Grytviken, Christen Christensen sent his floating factory ship *Admiralen* to the South Shetland Islands and started whaling in Admiralty Bay, King George Island. The next to appear in the South Shetlands was Adolf A. Andresen. He had already introduced modern whaling in Punta Arenas. Now he brought his new floating factory ship *Gobernador Bories* to Deception Island. This peculiar island was a perfect shelter from the rough Antarctic winds. Whalers Bay at Deception Island and Admiralty Bay at King George Island became the centres of whaling operations in the South Shetlands. In 1909 nine large factory ships moored along the shores of Whalers Bay—or "Factory Bay," as it was called at the time. Many factory ships also explored farther south along the Antarctic Peninsula. They came back year after year to sheltered bays and inlets such as Port Lockroy at Wiencke Island, Neko Harbour at Danco Coast, and many, many more. In the peak whaling season before World War I, twelve floating factory ships operated in the South Shetland whaling grounds.

Thus, while South Georgia became the center of shore station whaling, the South Shetland Islands became the center of whaling with floating factory ships. However, South Georgia was also visited by factory ships, and one shore station was erected in the South Shetlands—at Deception Island in 1912.

Shore station whaling also spread to other locations in the Antarctic area. At Îles Kerguelen (South Indian Ocean), a station was erected from 1908. At Signy Island in the South Orkney Island, where floating factories had been operating from 1912, a Norwegian company erected a small station in 1921.

Pelagic Whaling

In the mid-1920s a major transformation took place in the Antarctic whaling industry. The whalers had gradually diminished the whale stocks in the coastal waters of South Georgia and the South Shetlands. An expansion of the industry had also been restricted in these areas due to British sovereignty and concessions. The whalers therefore thought of ways to move their operations farther away from the shores into other parts of the Southern Ocean. Once again C. A. Larsen lead the way when he took a whaling expedition through the pack ice and into the ice-free Ross Sea in 1922.

Bringing the factory ships into the ice and moving them along the ice edge off shore demanded larger and better vessels. An important technological breakthrough was the whaling factory ship *Lancing,* which was equipped with a stern hauling-up slipway in 1925. The whales could then be hauled onto the ship's deck and processed in a much more efficient way than before—when the whales had been flensed along side as in the old whaling days.

The new whaling grounds and better technology led to a dramatic expansion in Antarctic whaling from the late 1920s. The industry had entered a new era, which has been characterized as "pelagic" whaling. The factory ships used for these operations were among the largest ships of the time. Some were rebuilt tankers or ocean-liners. Some were new, like *Kosmos* of 17,801 tonnes, built for Norwegian owners at Workman Clark, Belfast, in 1929. It signified a new design that from then on dominated the industry.

Pelagic whaling took the whalers away from the South Shetlands and the sub-Antarctic islands and all the way around the Antarctic continent. The whaling expeditions sailed along the northern extension of the ice and gradually moved south as the ice retreated throughout the southern summer. The main whaling grounds were in the Southern Ocean between South America and eastwards to Australia.

The industry grew towards the peak whaling season of 1930–1931. In that season forty-one floating factory ships and six shore stations operated, with about 200 catcher boats. The result was about 40,000 whales killed, producing more than 3 million barrels of oil. Never before or after were so many blue whales (29,410) killed in one season.

The whaling industry experienced the same turmoil as most other industries in the world economy in the early 1930s. In 1931 it was clear that the demand for whale oil could not match the record-high production, and most of the whaling fleet was left in the buoys for the 1931–1932 season. Shore stations closed down, and several companies permanently went out of business. With the exception of three stations at South Georgia (Grytviken, Leith Harbour, and Husvik Harbour), no Antarctic shore stations survived the economic crises. They were abandoned and left to decline.

The whaling industry revived in the late 1930s, and a record 46,000 whales were killed in the 1937–1938 season. But again the industry was brought to an almost complete standstill—this time by World War II. The whaling factory ships were used for the war effort on both sides as tankers and cargo ships. They faced heavy losses, and the world fleet of whalers was reduced by 1945 to less than half its prewar size. Many questioned whether the industry should be started up again. However, high demand and prices led to new expansion, and whaling again became a lucrative business for several countries. The result once more was an overexpansion, and collapse was inevitable. Diminishing catches and returns and increased international control gradually put an end to most commercial Antarctic whaling from the 1960s.

Whaling Nations

Norway was the pioneer nation of Antarctic twentieth-century whaling, and, together with Britain and Argentina, had the longest involvement in the industry. Argentina's activity was connected to one company that owned the Grytviken whaling station at South Georgia—a station primarily manned by Norwegian whalers. Norway and Britain, on the other hand, were the home countries of most of the major whaling companies. There were also strong ties between the two, and the period until the mid-1930s may be called the Norwegian–British hegemony of Antarctic whaling. From then on their dominance was challenged by new whaling nations, most importantly by Japan and Germany, which entered Antarctic whaling in the middle of the 1930s. Japan soon almost equalled the two whaling pioneers.

After World War II, the Netherlands (which had formerly been very active in Arctic whaling) went into the business. So did the Soviet Union, and, together with Japan, it took a leading role in Antarctic whaling in the 1950s and 1960s when British and Norwegian operations were gradually phased out. Several British and Norwegian floating factory ships and whale catcher boats were sold to Japanese whaling companies in the 1950s and 1960s.

Other countries that became involved in Antarctic whaling included Panama and the United States—but primarily as registries for whaling companies based in other countries. The United States, which had dominated global whaling in the nineteenth century, never became greatly involved in twentieth-century Antarctic whaling.

All nations except Japan and the Soviet Union abandoned Antarctic whaling in the 1960s. After the whaling moratorium of 1982, the Soviet Union gradually decreased its whaling, while Japan to this day has continued limited Antarctic whaling for small minke whales for scientific purposes. The Japanese, however, have announced intentions to increase their whaling activities.

Products

In old-style whaling, the main output was oil and whalebones (baleen). Oil from the blubber of the right whales and the case of the sperm whales was mainly used for lighting, lubrication, and producing soap. Whalebones were made into various products in the preplastic era. In the early days of Antarctic whaling, oil was still used for its traditional purposes, but the market had, to a large extent, been taken over by mineral oils. However, an important scientific discovery of the first decade of the twentieth century led to new uses of whale oil. The hydrogenation process allowed fluid oil to be transformed into solid fats. By this process, whale oil could be utilized as an edible fat and was able to be used for human consumption. It became an ingredient in several products. The main one was margarine, which became the single most important product of the industry during its heyday in the 1920s and 1930s, and again after World War II, when demand for edible fats was high in many countries.

In the initial years of Antarctic whaling, most expeditions primarily sought the oil-rich blubber. Soon, however, the remainder of the carcass, meat and bone, were also used to extract oil. This left remains that were ground and dried and made into the guano or whale meal used for animal food or as fertilizer. The shore stations, which had available space for such plants, particularly specialized in these products. A third product was frozen whale meat for human consumption. While this became a main product for the Japanese Antarctic whalers, European whalers only took up this product to a limited extent, especially after the 1950s, together with other so-called "byproducts" as meat-extracts.

How important in economic terms was the Antarctic twentieth-century whaling industry? Although whale oil never represented more than a fraction of the world supply of edible fats, it met a demand—particularly in Europe—in the interwar years and the early years after World War II, when there was a general shortage in supply. Whaling never became a very important industry of their home countries. The exception was Norway, a small economy with a disproportionately large share of the whaling companies and the employment, especially during the early industry and throughout the 1930s. Since most of the products went into the export markets, the currency income was of significance.

Work and Organization

A whaling expedition consisted of the floating factory ship or the shore station together with workers, crew, and catcher boats. In the early years, the number of catcher boats per expedition was not often more than two or three. After the Second World War, more than ten could be employed by one expedition. The crew likewise increased through the years as the vessels and stations grew larger, exceeding 300 per expedition. The whalers' payment was based on a lay system.

Antarctic whaling was, because of the climate, always undertaken on a seasonal basis—usually no longer than from October to April. Between the seasons, whalers left for their home countries. At the shore stations, a smaller maintenance crew usually stayed throughout the winter.

Whaling expeditions were dominated by men. Only on occasion did a few women (sometimes with children) stay at shore stations, usually accompanying the managers. The shore stations, especially the most developed ones at South Georgia, appeared as small industrial villages. The processing plant was the core of the station. There were also workshops, a small shipyard, living barracks, messes, storage facilities for provision and products, cinemas, cemeteries, soccer fields, and ski-jumps. The floating factory ships had, of course, more limited space, but basically performed the same core functions as the shore stations. The primary task was to process the whales that had been killed and towed in by the catcher boats. Blubber, meat, and bones were steam-cooked in different plants to extract the oil. Numerous methods were then used to purify the output, from clearing tanks to mechanical separators. The solids that remained were input in the production of the whale meal. Other plants took care of the byproducts. Whaling was indeed a sophisticated processing industry. If the expedition focused on frozen meat, as many of the Japanese whalers did, separate refrigerator vessels were employed.

Regulation and Control

For most of the period, Antarctic whaling faced regulations and control in one way or another. Almost from the beginning, the British government restricted the number of companies and the number of whale catchers that were allowed to operate in British territories. It also introduced legislation limiting the waste from the processed whales: full utilization was required.

The pelagic whaling of the late 1920s evaded these rules and led to a dramatic overexploitation. After the crises of the industry in the early 1930s, the two leading whaling nations, Britain and Norway, negotiated voluntary quota agreements between the whaling companies in an attempt to limit the catches. The number of expeditions was reduced. So was the size of the production. However, the expansion of the industry in the late 1930s, with new whaling nations entering the industry, undermined the regulations.

An important new phase of controlling the Antarctic whaling industry started with the establishment of the International Whaling Commission in 1946. From then on, restrictions on catches, season length, and catching areas were imposed. The commission decided on annual global quotas for the industry. In 1963 blue whales and humpback whales were protected. This was a long-overdue decision. The killings of blue whales had already peaked in 1931, indicating a diminishing of the stocks. After that time, whalers gradually shifted their attention to the smaller sei and fin whales—and in later years even to the small minke whales that no one had bothered to catch in the early years of Antarctic whaling.

Despite restrictions and reduced quotas, the exploitation of the whale stocks was too high even throughout the postwar years. The Antarctic whaling industry was finally more or less closed down, not because of restrictions but because of lack of whales and profitability for the companies involved.

The whaling industry—today and historically—has been criticised for lack of control and overexploitation. Whaling in Antarctica throughout the twentieth century obviously depleted the whale stocks to such an extent that it is uncertain whether they will ever recover. From this perspective, the history of whaling is a sad story. On the other hand, whaling was also an important industry of its day that generated useful products and employment. As in previous centuries, it was also a history of skills, exploration, and adventure.

BJØRN L. BASBERG

See also **Christensen Antarctic Expeditions (1927–1937); Christensen, Lars; Deception Island; Dundee Whaling Expedition (1892–1893); Foyn, Svend; Greenpeace; Kerguelen Islands (Îles Kerguelen); International Whaling Commission (IWC); Larsen, Carl Anton; Norwegian (Tønsberg) Whaling Expedition (1893–1895); Sealing, History of; South Georgia; South Shetland Islands; Southern Right Whale; Swedish South Polar Expedition (1901–1904)**

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WILD, FRANK

Frank Wild spent more time in Antarctica during the Heroic Age of Antarctic exploration than anyone else. Altogether he served on five Antarctic expeditions: the British National Antarctic Expedition of 1901–1904, under Robert Falcon Scott, Ernest Shackleton's British Antarctic Expedition of 1907–1909, Douglas Mawson's Australasian Antarctic Expedition of 1911–1914, Shackleton's Imperial Trans-Antarctic Expedition of 1914–1917, and the Shackleton-Rowett Expedition of 1921–1922. He also led the British government-sponsored mission to Spitsbergen in 1918–1919 after Shackleton, the original leader, was posted to northern Russia.

Wild's record is unique, yet there was nothing particular in his background to denote any special aptitude for or affinity with polar exploration. There was a belief in the family that Wild's mother was descended from Captain James Cook, and Wild was very proud of this relationship, although it proved untrue. The only other member of the Wild family to go on a polar expedition was Frank's younger brother Harry Ernest, who was a member of the ill-fated Ross Sea Party of the Imperial Trans-Antarctic Expedition.

John Robert Francis Wild was born on April 10, 1873, the second of thirteen children born to Benjamin and Mary Wild. Benjamin Wild was a school teacher, originally in Yorkshire, where Frank was born. In 1888 Wild joined the merchant navy, in which he served for 12 years. In 1900 he joined the Royal Navy, and soon after he saw the notice that Scott was looking for volunteers for the Antarctic expedition in *Discovery*. Wild was one of 6000 in the Royal Navy to apply and—as he was just under 5 feet 5 inches tall—was surprised to be accepted.

Wild made a number of significant contributions to the *Discovery* Expedition, including leading several of his comrades back to base in terrible weather and harrowing circumstances after one of them, George Vince, fell to his death. Scott spoke highly of Wild's service and recommended him for promotion, which followed with Wild's elevation to the rank of petty officer.

On that expedition, Wild had struck up a friendship with Shackleton, the third lieutenant. In 1907 Shackleton specifically asked Wild to join his British Antarctic Expedition in *Nimrod.* Wild was one of three men who accompanied Shackleton on the southern journey, attaining a point only 97 geographical miles (112 statute miles or 180 km) from the South Pole. It was that experience that made Wild "a Shackleton man." Upon his return home, Wild bought himself out of the Royal Navy. When Scott later asked Wild to join his second Antarctic expedition he declined. Scott, he felt, was "too much the navy man." Instead, he accepted Douglas Mawson's invitation to join his Australasian Antarctic Expedition, which was to explore as much as possible of the coastline of the "Australian Quadrant" of Antarctica, that area south of Australia.

Mawson wrote about his decision to take Wild in his book *The Home of the Blizzard:* "Wild had already distinguished himself in the south on both the Scott and Shackleton expeditions. He is now in the position of being, as it were, the oldest resident of Antarctica. Our sojourn together at Cape Royds, as fellow members of the Shackleton expedition, had acquainted me with Wild's high merits as an explorer and leader."

Wild was in command of the Western Base, which included seven other men, all either Australian or New Zealanders, none of whom had been to the polar regions before. Six of them were under the age of 26, and five were university educated. The party was landed from *Aurora* on an ice shelf (now named the Shackleton Ice Shelf) more than 1000 miles (1600 km) away from Mawson's main base at Commonwealth Bay. The shelf could have calved away and the party been swept out to sea, but Wild took full responsibility for the decision to land.

Wild's party was there for 1 year. They made six separate sledge journeys, mapped some 350 miles (560 km) of coast line, went inland onto the plateau, visited the extinct volcano Gaussberg, and made valuable meteorological, biological, and geological studies. There were no casualties, the party had no major internal strife, and all members spoke highly of Wild's leadership.

Shackleton then asked Wild to be second-in-command of his Imperial Trans-Antarctic Expedition, which was to cross Antarctica from Vahsel Bay in the Weddell Sea to the Ross Sea. Wild's participation was crucial: in the months spent on the ice while *Endurance* was trapped, in the boat journey to Elephant Island, and then, most important of all, for the 4 and a half months in 1916 when Wild was the leader of the remaining 21 men of the expedition waiting for rescue while Shackleton sought help. To maintain the health and morale of the disparate group of men for that period when they had no idea if Shackleton would ever return, were short of food, and had little chance of being able to achieve any rescue themselves, was an example of leadership second only to Shackleton himself.

On his return to England, Wild volunteered for war service. He was given a temporary commission in the Royal Naval Reserve, sent on a Russian language course, and posted to Archangel as RN transport officer during the time of the British intervention in the Russian Civil War. He was there for 1 year, and then Shackleton asked for him to join him on a mission to Spitsbergen to establish a British and Allied presence there and forestall any attempt by Germany to set up a base. Before they reached Spitsbergen, however, Shackleton was recalled to Murmansk, and Wild became the mission leader. He was in Spitsbergen for 12 months, most of the time searching for mineral deposits, as the Germans had already abandoned any idea of establishing a military presence there.

Wild went to Nyasaland in 1920 (with James McIlroy, one of the surgeons from *Endurance*). While there, he received a telegram from Shackleton asking him and McIlroy to join him on another Antarctic expedition, in a small ship, *Quest*. They did, but Shackleton died on board at South Georgia in January 1922 and Wild took command. The purpose of the expedition had never been hugely clear, but Wild got the assent of the other nineteen members to carry on. They went along the coast of Antarctica, landed on Elephant Island (although not the side where the *Endurance* party had spent 4 and a half months), visited several other Antarctic islands, and arrived back in England 12 months after they had left. With no coherent plan for the expedition, a small ship, bad weather, and inadequate equipment, it took both skill and firmness to ensure that the expedition achieved what it did.

Quest returned to England in September 1922. Five weeks later Wild married Vera Altman (whom he had met in Archangel after she had travelled across Russia from Vladivostok), and the following year they emigrated to Natal. Wild's attempts at farming there failed, and he took a variety of jobs in Rhodesia, on the border of Swaziland, and in the Transvaal. In 1928 he was divorced, but three years later he married Beatrice Rowbotham, a South African woman. He had little capital and at one point considered selling his Polar Medals and his other medals to raise money.

Eventually in 1939 the British government awarded him a small pension, but he died shortly afterwards of pneumonia, in Klerksdorp, Transvaal, on August 19, 1939. He was cremated at Braamfontein Cemetery in Johannesburg.

Most leaders and other major figures on Antarctic expeditions have been criticised (sometimes severely) in written accounts, diaries, or memoirs. Virtually never, however, was there any criticism of Wild's role, work, or leadership in any of the expeditions in which he participated: a unique tribute for a unique man.

LEIF MILLS

See also **Australasian Antarctic Expedition (1911–1914); British Antarctic *(Nimrod)* Expedition (1907–1909); British National Antarctic *(Discovery)* Expedition (1901–1904); Mawson, Douglas; Ross Sea Party, Imperial Trans-Antarctic Expedition (1914–1917); Scott, Robert Falcon; Shackleton, Ernest; Shackleton–Rowett Antarctic Expedition (1921–1922)**

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WILKES, CHARLES

American naval officer Charles Wilkes (born April 3, 1798, in New York City) commanded the US Exploring Expedition of 1838–1842—the first voyage of discovery funded by the US government—which surveyed vast tracts of the Pacific Ocean, the Pacific Northwest of North America, and a 1500-mile stretch of Antarctic coastline fronting on the Indian Ocean, now known as Wilkes Land. Wilkes has also been credited as the first person to recognize Antarctica as a continent.

The youngest of four children of a successful businessman, Wilkes lost his mother before he was 3 years old. After attending several boarding schools, he became interested in following the sea. He made two transatlantic merchant voyages, then obtained a midshipman's warrant in the US Navy in 1818, rising to lieutenant in 1826.

On his early naval voyages, Wilkes developed skills in astronomy, geodesy, and hydrography, particularly during a survey of Narragansett Bay in 1832–1833. In 1833, he was put in charge of the Depot of Charts and Instruments, the forerunner of both the Naval Observatory and the Navy Oceanographic Office.

Wilkes sailed to Europe in 1836 to purchase instruments for the US Exploring Expedition, which Congress had authorized that May. While in Europe, he met and worked with many of the leading scientists of the day. Upon his homecoming in early 1837, however, the expedition was in disarray, so Wilkes spent that summer and fall surveying the Georges Bank and the spring of 1838 surveying the Savannah River area.

After several more senior officers had declined or been relieved of the command, Wilkes was offered leadership of the Exploring Expedition in March 1838. His brother-in-law, noted engineer James Renwick (Wilkes had married Jane Renwick, a childhood friend, in 1826), proved an important advocate for Wilkes within the political establishment and helped him gain the position.

Despite protests by many jealous senior officers, Wilkes was the best-suited officer in the US Navy for the task, thanks to his surveying expertise and his work with many prominent scientists. He moved quickly to prepare and outfit the squadron's six vessels, select the officers and men, and trim the overly large scientific staff.

The expedition sailed from Hampton Roads, Virginia on August 18, 1838. When it returned 4 years later, unfortunately, its many important accomplishments were overshadowed by a web of courts-martial between Wilkes and four of his officers. Wilkes was widely considered a vain, arrogant, and punitive leader, but he was convicted of just one charge: illegally flogging some of his men.

Although the expedition was greeted largely with indifference in the United States upon its return, Wilkes was awarded the Founder's Medal of the Royal Geographical Society in 1848. Promoted to rear admiral on the retired list in 1866, Wilkes died on February 7, 1877, at his home in Washington, D.C.

Wilkes' greatest legacy is the Exploring Expedition's nineteen reports, on which he worked indefatigably from 1844 to 1861, writing seven himself (the five-volume *Narrative* as well as the reports *Meteorology* and *Hydrography*), while overseeing production of the other dozen.

JEFF RUBIN

See also **British Antarctic (*Erebus* and *Terror*) Expedition (1839–1843); Dumont d'Urville, Jules Sebastien Cesar; French Naval (*Astrolabe* and *Zélée*) Expedition (1837–1840); Ross, James Clark; United States Exploring Expedition (1838–1842)**

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WILKINS, HUBERT

Sir George Hubert Wilkins (October 31, 1888–December 1, 1958), Australian polar explorer, photographer, cinematographer, pioneer aviator, balloonist, naturalist, newspaper reporter, navigator, submariner, and decorated war hero, was born at Mount Bryan East, South Australia. He studied engineering at the School of Mines in Adelaide but shifted fields entirely and became a cinematographer for the Gaumont Company and a reporter for the *Daily Chronicle* of London. Wilkins learnt to fly, and in 1912 was despatched by the Gaumont Company to film moving images of the war in the Balkans. In 1913 he took the post of cinematographer on Vihljalmur Stefanson's Canadian Arctic Expedition (he allegedly misread a telegram and mistakenly thought that it was an Antarctic expedition) and by early 1916 had returned to Australia to join the Australian Flying Corps as a lieutenant. His new role was to assist Captain Frank Hurley (photographer on Douglas Mawson's Australasian Antarctic Expedition and Ernest Shackleton's Imperial Trans-Antarctic Expedition) in filming hostilities in World War I France for use in newsreels. Despite his refusal to carry firearms, he twice earned the Military Cross, first for his attempts to rescue wounded men at the Third Battle of Ypres, and later for leading a company of American soldiers.

It was Wilkins' fascination for aviation and photography that inspired his first real brush with Antarctic exploration. Inspired by Hurley's achievements, he felt sure that a combination of aerial photography coupled with the great distances that could be travelled rapidly by aeroplane could significantly enhance the potential for Antarctic discovery and exploration. He participated in the British Imperial Expedition (1920–1922), organised by John L. Cope, which aimed to make a successful transpolar flight using two aircraft for the attempt with a further twelve support aircraft. The expedition began in the spring of 1920 but failed to secure adequate funding or the necessary aircraft, relegating its endeavours to a 4-month fact-finding trip in Andvord Bay and the west coast of Graham Land on the Antarctic Peninsula. Undeterred, Wilkins left the expedition early and approached the US representative for Junkers aircraft to secure the loan of three aircraft for a further expedition. However, his plans were shelved when Wilkins instead agreed to accompany Shackleton as naturalist on what was to be Shackleton's last Antarctic expedition. The expedition, which had scientific objectives, continued after Shackleton's death under the command of Frank Wild and afforded Wilkins the opportunity for further Antarctic experience and to photograph flora and fauna on South Georgia.

In 1925, Wilkins again tried to realise his dream of aerial exploration with the Australasian Polar Pacific Expedition. However, its aim to fly from the Ross Sea over King Edward VII land to Graham Land was again frustrated by lack of funds. With funding a recurring difficulty, Wilkins sought to raise his credibility and public profile between 1925 and 1928, by joining with Carl Ben Eielson (1897–1931) in a series of Arctic endeavours. Eielson's 2200-mile (3450-km) flight from the North Slope of Alaska over the polar ice cap to Greenland was the first flight from North America over the North Pole to Europe. Eielson was decorated with the Distinguished Flying Cross and won the Harmon Trophy for the greatest American aviation feat of the year. Wilkins received the Morse Medal from the American Geographical Society, the Patrons Medal from the Royal Geographical Society, and a knighthood from King George V. Armed with these new honours, Wilkins again tried to attract finance for an Antarctic expedition. With Eielson he had demonstrated the efficacy of aerial reconnaissance in the Arctic as a tool for exploration. Together they had charted hundreds of miles of new terrain and corrected existing maps to exclude phantom landmasses claimed by earlier explorers.

Initially Wilkins approached R. G. Casey, a major in the Australian army and an official at the London High Commission, but his argument for an Antarctic expedition to establish strategic weather stations on the Antarctic rim failed to secure funding. Instead, William Randolph Hearst, the millionaire American publisher, paid US$25,000 for exclusive media rights to an Antarctic expedition that consequently became known as the Wilkins-Hearst Antarctic Expedition.

The expedition's pilots once more comprised Wilkins and Eielson, with the addition of Joe Crosson, an experienced Arctic pilot who had been the first to fly an open plane between Fairbanks and Point Barrow, Alaska, and to land on a glacier. The trio used the same well-proven Lockheed Vega aircraft (with its name now changed to *Los Angeles*) as was flown during the Wilkins-Eielson Arctic endeavours of 1928. The seasoned Vega became the first plane to be flown in the Antarctic and was backed up by a second Vega dubbed *San Francisco*. In addition, the expedition received $10,000 of equipment from Australia's Vacuum Oil Company, while the Norwegian N. Bugge Hektor Whaling Company provided sea transport. Crucially, Heintz and Kaufman of San Francisco equipped the planes with shortwave radio equipment that furnished long-range communication and served as a radio distress beacon when the Morse key was depressed continuously.

Before leaving the Falkland Islands (their final port before Deception Island), Wilkins received instructions from the governor to make territorial claims to the Falkland Islands Dependency, which included Deception Island. From Deception Island, Wilkins hoped to explore Graham Land and the Palmer Peninsula (parts of what is now known as the Antarctic Peninsula) as far as fuel and weather permitted. However, his grand design was to fly to the Weddell Sea from Deception Island and then across the Antarctic continent (later achieved by Lincoln

Ellsworth) to the Ross Sea and Framheim, Roald Amundsen's base camp on the Ross Ice Shelf during his South Pole expedition. On December 20, 1928, Wilkins and Eielson flew *San Francisco* for 10 hours above Hughes Bay, across Gerlache Strait, and close to the Danco Coast before crossing the Peninsula from west to east. Beyond 67° S they discovered and named a series of channels and dropped a territorial claim on behalf of the British government. Running short of fuel, they then turned around at 71°20′ S. During their flight Wilkins took only 20 minutes to sketch 40 miles of unknown territory in addition to photographing their flight with a Kodak 3A folding autographic camera (using 122 roll film) and two movie cameras. In just 10 hours their 1300-mile (2100-km) flight charted nearly 1000 miles (1600 km) of terra incognita and marked the first time that undiscovered land was mapped from a plane. The expedition's final flight, on January 10, 1929, flew 250 miles (400 km) south to confirm their previous aerial sightings.

In November 1929, the second Wilkins-Hearst Expedition returned to Deception Island, aided by £10,000 from the Colonial Office and transported by the Discovery Committee's research ship, *William Scoresby*. The expedition pilots comprised Wilkins, Al Cheeseman, an experienced Arctic pilot, and Parker D. Cramer (1896–1931), pioneer of the "Great Circle" route. The expedition's final flight reached 73° S but made only one substantial new finding between December 27 and December 29, Wilkins' discovery that Charcot Land (as it was known) was an island, which Wilkins claimed for Britain.

In the 1930s, Wilkins organised three expeditions for American millionaire Lincoln Ellsworth (1880–1951). He participated in Ellsworth's attempts to fly across the Antarctic continent from 1933 until Ellsworth finally succeeded on November 22, 1935. In 1957 Wilkins made his last journey to Antarctica as a guest of Operation Deepfreeze. He died the following year and his ashes were scattered at the North Pole.

Ian N. Higginson

See also **Antarctic Film; Antarctic Peninsula; Aviation; British Imperial Expedition (1920–1922); Deception Island; Ellsworth, Lincoln; Norwegian *(Fram)* Expedition (1910–1912); Photography, History of in the Antarctic; Shackleton, Ernest; Shackleton–Rowett Antarctic Expedition (1921–1922); South Georgia; Wild, Frank**

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WILSON, EDWARD

Edward Adrian Wilson was born on July 23, 1872 at Cheltenham, the son of Dr. Edward Thomas Wilson, a well-known local physician, and his wife Mary Agnes, who wrote a popular textbook about poultry keeping. Educated at Cheltenham College and Cambridge University, he qualified as a Bachelor of Medicine from St. George's Hospital, London. As a boy, he showed a great interest in the flowers and wild creatures of the countryside, as well as an ability to draw. He was later inspired by the paintings of J. M. W. Turner and others in the National Gallery, so that, when appointed to the British National Antarctic Expedition (1901–1904), he not only took on a medical role and that of vertebrate zoologist but also that of artist. During the expedition in *Discovery,* he took part in the southern journey (the first major inland penetration of the continent) with Robert Falcon Scott and Ernest Shackleton. During this, despite being disturbed at points by snow-blindness, he sketched the length of the previously undiscovered range of mountains that flank the western edge of the Ross Ice Shelf. These panoramas and his observations of whales, seals, penguins, and seabirds were published in the volumes of scientific results. Before the departure of *Discovery* he had written up the collection of Antarctic seals from the *Southern Cross* expedition of 1898–1900 for the British Museum (Natural History).

On the expedition's return, Wilson was appointed to the Board of Agriculture's Grouse Disease Inquiry. He wrote one-third of the resulting report and illustrated it in its entirety. He sailed again for the Antarctic in June 1910 as head of the scientific staff during Scott's second and last expedition in *Terra Nova*. His nickname was "Uncle Bill." He inspired great respect and affection and was rarely too busy to advise or to help other members of the expedition. As during the British National Antarctic Expedition, he contributed himself—under the pseudonym "Zingiber" (Ginger, from the colour of his hair)—and illustrated most of the articles and poems by others for *The South Polar Times,* published in facsimile in 1907 and 1914. He also completed more fine watercolours, a selection of which was reproduced in the narratives of both expeditions and in the volumes of scientific results. His winter journey to Cape Crozier on the far side of Ross Island in June 1911, with Henry R. Bowers and Apsley Cherry-Garrard, to investigate the breeding habits of the emperor penguin, was made famous by the publication of Cherry-Garrard's book *The Worst Journey in the World.* Wilson was to die in the tent with Scott and Bowers in March 1912 during the desperate return journey from the South Pole. "I can do no more to comfort you," wrote Scott to Wilson's wife, Oriana, while the blizzard raged, "than to tell you that he died as he lived, a brave, true, man—the best of comrades and the staunchest of friends."

Bequeathed by his widow, the bulk of Edward Wilson's watercolours and sketches, as well as his *Discovery* diary, are in the Scott Polar Research Institute, Cambridge. There are still many admirers of his life and work.

ANN SAVOURS

See also **Art, Antarctic; British Antarctic *(Southern Cross)* Expedition (1898–1900); British Antarctic *(Terra Nova)* Expedition (1910–1913); British National Antarctic *(Discovery)* Expedition (1901–1904); Ross Island; Scott, Robert Falcon; Shackleton, Ernest**

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WILSON'S STORM PETREL

Wilson's storm petrel *(Oceanites oceanicus)* is a small sooty-black storm petrel with a white rump, a pale upper-wing bar, and long black legs and feet with yellow webs. It is a member of the family of tube-nosed seabirds (Procellariiformes), which also includes albatrosses, shearwaters, and other petrels. They are completely dependent on marine prey and only return to land to breed. Other typical features of the family, which are shared by Wilson's storm petrels, are a long lifespan, with an adult mortality of less than 10%, and low reproductive rate. Wilson's storm petrels are the smallest endothermic animal of the Antarctic, only 18 cm long from bill to tail and 34–45 g in body mass, and thus must be particularly well adapted to withstand the frequent subzero temperatures at their breeding sites. In southern populations of the subspecies *O. o. exasperatus,* the body size and body mass are increased compared with the more northern subspecies, *O. o. oceanicus*.

Wilson's storm petrel has repeatedly been claimed to be the most numerous of all bird species worldwide. However, there seems no particular reason to believe this, as several other species also have a total population of several million pairs. Despite its abundance and familiarity to fishermen for centuries, the breeding grounds of Wilson's storm petrels were long unknown, until the first nests were found on sub-Antarctic Îles Kerguelen in 1874. Not until the era of Antarctic exploration at the beginning of the twentieth century was the extensive circumpolar breeding distribution revealed. The breeding sites for *O. o. exasperatus* include nunataks, snow-free coasts and islets around the whole of the Antarctic continent, and the islands of the Scotia Arc. In the sub-Antarctic, breeding grounds of *O. o. oceanicus* are found at South Georgia, the Falkland Islands, islands close to Cape Horn, Heard Island, Îles Crozet, and Îles Kerguelen. Estimates of the breeding populations at all sites are gross or incomplete, as surveys are extremely difficult, and few detailed estimates have been attempted. During the nonbreeding period, Wilson's storm petrels migrate north, visiting all major oceans except the Arctic. They reach the North Atlantic Ocean as far north as Newfoundland but are less numerous in the North Pacific Ocean, where they reach 30° N during the Southern Hemisphere winter.

Wilson's storm petrels feed at the sea surface, mainly while on the wing. During the breeding season, they frequent cold waters over the continental shelf or inshore and can detect food by smell. They prey on a wide variety of zooplankton including krill, amphipods, and small swarming fish, with smaller quantities of copepods, gastropods, and cephalopods. During the breeding season, krill (*Euphausia* spp.) is the most frequent prey. Chick-provisioning adults take more fish than incubating adults or nonbreeders, suggesting that adults selectively choose fish as an important source of nutrients for the growing chick. Because of their small size, Wilson's storm petrels have high energy requirements for maintenance and growth, and need to consume over 120% of their body mass in krill each day to meet their own demands and feed the chick.

Wilson's storm petrels may be encountered solitary or in feeding flocks of hundreds of birds. Their characteristic pattering flight consists in a series of short glides interspersed with fluttering and hovering to feed in one spot. Because they have very low wing loading, the flight is aerial, with frequent leaps several metres high. The bird has been named "skipjack bird" for this in Tristan da Cunha. Wilson's storm petrels may follow ships to seek organisms churned up by the propeller or scavenge scraps of fishing discards from vessels.

Like at sea, at the breeding grounds Wilson's storm petrels are both solitary and colonial, with single nests encountered and loose or dense colonies. Suitable snow-free and protected nest sites are typically in limited supply. The birds breed mainly in natural crevices such as cracks of cliffs and among boulders of rock slopes but have also been found to excavate burrows in soft soil and moss banks. Several studies of the breeding biology have been carried out since the pioneering study on the Argentine Islands in 1934–1937, but unfortunately no long-term data set is available from any of the study sites. An ongoing study at King George Island (South Shetlands) started in 1996.

Breeding starts in November to December, when adults between 3 and about 30 years of age return from the wintering grounds and reoccupy their burrows. At Antarctic colonies such as the South Shetland Islands, the nest chambers are still filled with ice when the first adults arrive. The ice beneath the rocks that form the breeding cavities melts during November and early December, when the temperatures exceed 0°C on most days. About 10 days before egg-laying, the female departs from the colony to feed intensively while the large egg (11 g, ~28% of adult body mass) is formed. The first eggs are laid in mid-December, and in January most of the breeding birds are incubating. The species has a socially and genetically monogamous mating system with intensive biparental care during incubation and chick-feeding. The single white egg is incubated in stints of c. 2 days but is often intermittently incubated if food abundance is not high. Remarkably, the egg can survive for several days if it cools to ambient temperature. The incubation time varies according to the number of days the egg is left unattended, from 39 to 59 days. Most chicks hatch in the first half of February. The hatchlings weigh only 6 g and are brooded for 1–4 days but left unattended in the burrow during the day when only a few days old. Both parents feed the chick with partly digested, regurgitated meals collected during feeding trips within a radius of over 200 km around the colonies. Each parent attends at a mean interval of 2 days until fledging, but in poor conditions, chicks may be fed more sporadically. Older chicks may fall into torpor and survive up to 1 week without food, while younger chicks starve quickly if not fed regularly. In good conditions, in contrast, chicks may accumulate subcutaneous fat and stomach oil and reach up to twice the body mass of adults.

The breeding adults visit the colonies, mate, and feed their chicks at night in order to reduce the chance of predation by skuas *Catharacta* spp. However, some skuas with established territories close to a colony of Wilson's storm petrels can become very skilled in catching birds on the wing even in poor light conditions and may leave their territory littered with pellets containing the remains of storm petrels.

The fledging period varies with latitude, taking between 48 days in southern colonies and 78 days farther north. The short fledging period in southern colonies indicates that the feeding rate is higher farther south, where there may be more abundant food supplies (or a shorter window for breeding). However, southern breeding places have another disadvantage. In Antarctic colonies, the nests are frequently snowed in, with snowstorms possible during all stages of the breeding season. Chicks with a good reserve of fat can survive entombment by snow, and parents dig tunnels through soft snow and feed the chicks. However, the snow frequently starts thawing during the day and subsequent frost results in a hard sheet of ice over the drifted snow, effectively blocking the nests.

For communication in the darkness of the breeding burrows at night, Wilson's storm petrels rely mainly on olfaction and calls. Adults use grating calls and male-specific chattering calls in mate attraction, mate recognition, and burrow defence, and peeping calls are uttered by both genders, especially in response to handling. Chicks call similarly to the peeping call of adults, especially while the parent is in the burrow, and these calls seem to play the role of an appeasement contact call. A second type of chick call is used exclusively for begging for food and is used at a greater rate by hungrier chicks. Parents respond to increased begging by regurgitating larger meals. Like other small burrowing petrels, Wilson's storm petrels have a characteristic musky smell, which is also apparent in the nesting material. Adult storm petrels use olfaction to locate their nest burrows, and chicks smell their way back to their individual burrows after excursions in the nights preceding fledging.

The breeding success of Wilson's storm petrels is highly variable and depends on the availability of prey and meteorological conditions. Krill forms the base of the feeding ecology of this bird; thus, competition with commercial fisheries is a potential threat, especially the large-scale exploitation of krill. Krill abundance may also be influenced indirectly by humans, for instance, if global warming leads to changes in oceanography and a reduction in the extent of Antarctic sea ice in winter. Sea ice is vital for the over-winter survival and reproduction of krill, and the storm petrels have low breeding success after low winter sea-ice cover. At the breeding sites, there are two potential threats: at some sub-Antarctic colonies (Îles Crozet, Îles Kerguelen, Falkland Islands), birds are subject to predation by introduced predators such as cats *Felis catus,* rats *Rattus* spp., and mice *Mus* spp., while in Antarctic colonies, snowstorms occur during the summer, burying burrows. In the South Shetland Islands, for example, the prevailing wind direction during the breeding season is westerly, whereas easterly winds are associated with snowstorms and may lead to entombment and complete breeding failure of entire colonies.

Petra Quillfeldt

See also **Crozet Islands (Îles Crozet); Kerguelen Islands (Îles Kerguelen); King George Island; Petrels: Pterodroma and Procellaria; Seabird Conservation; Seabird Populations and Trends; Seabirds at Sea; Skuas: Overview; South Georgia; Zooplankton and Krill**

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WIND

In Antarctica, the near-surface wind field is one of the most intensively studied meteorological elements. Early explorers acknowledged the strength and persistence of the wind. The extreme wind conditions largely restricted their field operations, as they still do today. During storms, snow is lifted into the air and deposited elsewhere. For this reason, field parties often need to dig out their transportation vehicles and tents in order not to be buried under a load of snow. The time-varying wind field determines not only the snow transport but also the transport of biological and chemical species and is therefore a meteorological element that is relevant to a wide range of studies.

Wind is the movement of air from areas of high pressure to areas of low pressure. There are several characteristic wind regimes in Antarctica. Extensively studied is the katabatic wind system, characterized by a low-level wind speed maximum and by a large directional constancy. Most landmasses on Earth gain heat during the day, leading to turbulence and convective activity, and they lose heat during the night, which suppresses the turbulence. In contrast, at high latitudes during winter, the radiational cooling of the surface lasts for the entire 24-hour period. The surface is colder than the overlying air. As a response, transfer of heat from near-surface air parcels towards the surface takes place. The density of the cooled air parcels is higher than the density of the surrounding warmer air. The parcels are heavier than their surroundings and, if a surface slope is present, the air will start to flow down the slope. In summary, the katabatic forcing occurs as a response to the transfer of heat from the near-surface layer due to radiational cooling of a sloping surface.

Pure katabatic winds occur when two forces balance, namely the katabatic forcing and the friction, a resistive force originating from the airflow over a rough surface. Pure katabatic winds are strong and blow parallel to the fall line on the steep slopes near the coast. Inversion winds occur when the katabatic force is balanced by the Coriolis force, which is related to the rotation of the earth. Inversion winds tend to be weaker and flow along the height contours on the gentle slopes in the interior. Often, all three forces mentioned above play a role, and the wind vectors are deviated to the left of the fall line by 20°–50°. In coastal regions, the piling up of cold air over the ice shelves and the sea ice can establish an opposing force, and in this case katabatic airflows do not penetrate far over the ice shelves and the sea ice.

Apart from the distinction between inversion and pure katabatic winds, there is also a distinction between ordinary and extraordinary katabatic winds. Regions where ordinary katabatics dominate are characterized by high wind speeds or gusts alternating with periods that are calm. In contrast, extraordinary katabatic winds blow uninterrupted for days or weeks. These winds are (in)famous due to the stories from early explorers, such as Sir Douglas Mawson, who wrote the well-known book *The Home of the Blizzard*. Extraordinary katabatic wind regimes are located in regions with upstream confluence of cold air into major drainage valleys, for example, upstream of Terra Nova Bay, Cape Denison, and Port Martin in Adélie Land, where the annual mean wind speed is about 20 m/s (eight on the Beaufort scale).

The katabatic circulation is so powerful and persistent that it affects the circulation in the entire free troposphere, roughly the first 8 km of the atmosphere above Antarctica. The katabatic outflow of mass in the lower atmosphere must be compensated for by downward motion (subsidence) and inflow of mass in the free troposphere.

Near-surface winds are not only driven by the katabatic forcing but also by pressure systems, such as depressions and synoptic weather systems. The circumpolar trough is a region of low pressure over the Southern Ocean (between 60° and 65° S), separating a zone of westerlies to the north from the polar easterlies to the south, close to the Antarctic continent. The eastward-migrating depressions in the circumpolar trough affect the weather at the coast profoundly and often cause strong winds. Near-surface winds related to pressure systems are largely affected by the orography and often flow along the orography. It is therefore very difficult to distinguish them from the winds generated by katabatic forcing. In the interior of the continent, the large-scale pressure gradient force is of equal importance to the katabatic force during the winter season, with both forces acting in the same direction.

Barrier winds occur when a cold airstream does not have sufficient kinetic energy to cross a barrier, and consequently flows parallel to the barrier. Barrier winds occur frequently along the Antarctic Peninsula and the Transantarctic Mountains. When the warm air overlaying the blocked cold air is able to flow over the barrier, warm downslope föhn winds occur at the lee side. During such events, the air is relatively warm and dry, and sublimation of blowing snow occurs.

Compared to other regions of the world, the history of measuring the near-surface winds in Antarctica is short. The first reports came in the beginning of the twentieth century from early explorers, who documented the extreme wind conditions in the regions where they traveled. During the first half of the century, measurements were made at sites scattered around the continent. Since the International Geophysical Year (1957–1958), which greatly contributed to our knowledge of Antarctic meteorology, more systematic measurements of the wind speed and direction became available. In the 1960s, a major step forward was made in producing an Antarctic-wide map of near-surface wind directions using sastrugi orientations. Sastrugi are sharp, irregular ridges formed on a snow surface by wind erosion and deposition and are therefore useful indicators of prevailing wind direction in remote regions. Aerial photographs of sastrugi fields provided the first broad-scale indication of the wind directions.

Most of our current knowledge of the near-surface wind field over land is from Automatic Weather Stations, consisting of a mast with arms on which wind direction (vane) and wind speed sensors are mounted. Information at higher levels is known from radiosonde balloon launches. Over the ocean, measurements have been made using drifting buoys. Apart from these *in situ* measurements, remote-sensing instruments have also been used in the last decades. The wind speed over the ice-free ocean is obtained from passive and active microwave instruments on different satellites. Satellite observing systems in the visible part of the spectrum have been used to estimate the upper-level wind by tracking clouds in images. Ground-based remote sensing instruments (Doppler Sodars and Radio Acoustic Sounding Systems) have been relevant to associate turbulence in the atmosphere to the near-surface wind system.

Another source of information on the wind field is from numerical models. Elegant one-layer models have shown that a steady-state wind develops when a sloping terrain is cooled, and these models have greatly contributed to our understanding of the katabatic wind system. Weather forecast models and climate models have been used to study the complex interaction between near-surface wind and a wide range of meteorological processes.

The winds interact strongly with other meteorological phenomena in the Antarctic region. During episodes of strong katabatic wind under clear sky conditions in winter, the turbulent exchange of heat between the surface and the overlying warmer atmosphere is large. Therefore the surface temperature is relatively high when compared to areas where winds are weak. The fast-flowing katabatic streams with their relatively high surface temperatures can be identified from satellite thermal infrared images. Also, the barrier and föhn winds have a strong effect on the local temperature, where barrier winds are generally cold due to the advection of continental air, and föhn winds are warm.

Winds are of major importance for the air–sea interaction. They are the major force for near-surface ocean currents. For example, the Antarctic Circumpolar Current in the Southern Ocean at about 40°–60° S is caused by the strong atmospheric westerlies in this region. When the ocean is covered with sea ice, leads or polynyas (areas of open water) form as a result of persistent offshore flow. In regions where the extraordinary katabatic winds prevail, like Terra Nova Bay, polynyas form every year at the same location. Also, the barrier and föhn winds in the Antarctic Peninsula have a large effect on the sea-ice distribution. Föhn winds force the ice away from the Larsen Ice Shelf and the barrier winds drive the ice northwards for a distance of 400 km, into the Antarctic Circumpolar Current.

The changes in sea-ice cover largely influence the exchange of heat and moisture between ocean and atmosphere, since sea ice acts as an insulator for the ocean. As very cold continental air flows over open water, exceptionally large heat fluxes cool the surface waters, leading to the formation of sea ice. This cooling brings about a destabilization of the water column and therefore induces downward convection. The associated changes in temperature and salinity affect the potential energy available in the oceans, which in turn drives the thermohaline circulation. In addition, leads or polynyas are believed to exert an important control over the ocean circulation beneath the ice shelves and hence the melting rate of the ice shelves.

Winds are of importance for the transport of chemical and biological species in the atmosphere. Depressions near the continent are associated with an influx of species from the ocean and from the neighboring continents. The atmospheric circulation pattern determines how a particle is transported from the source to the sink region and determines the deposition at the snow surface. Signals measured in ice cores have therefore often been used to obtain knowledge about the past state of the atmosphere. For example, increased dust content in the ice from the Last Glacial Maximum has been attributed to a more vigorous climate. The occurrence of pollen from non-Antarctic plants trapped in moss cushions and the presence of exotic plants and microorganisms on volcanically warmed Antarctic soils show that long-distance transfer of biological species takes place. Episodes of winds flowing off the high continental plateau toward the coast may inhibit transfer of species towards inland sites.

Strong winds that flow down the steep slopes towards the coast carry huge amounts of snow. Both this transport and the sublimation of blowing snow affect the net input of mass at the surface of the ice sheet (surface mass balance). Drifting snow is the transport of fine snow particles in the lowest layer above the surface, whereas blowing snow refers to conditions with a more vehement type of wind-driven snow, with a vertical extent of up to a couple hundred meters and strongly reduced visibility. At Mizuho, blowing snow occurs during 60% of the days in the winter season, and at another 30% drifting snow occurs.

Strong winds affect the heat loss of the body in inclement weather. For various combinations of wind speed and air temperature, the associated heat loss can be expressed as a wind-chill factor. In Antarctica, high winds are probably a limiting factor for outdoor activity more than low temperatures, as can be illustrated with a quote from C. T. Madigan (1929), participating in Mawson's expedition: "For nine months of the year an almost continuous blizzard rages and for weeks on end one can only crawl about outside the shelter of the hut, unable to see an arm's length owing to the blinding drift snow." The strong winds prevailing in the Antarctic can generate great problems for human activity in this region.

NICOLE VAN LIPZIG

See also **Australasian Antarctic Expedition (1911–1914); Climate; Clouds; International Geophysical Year; Mawson, Douglas; Sea Ice, Weather, and Climate; Synoptic-Scale Weather Systems, Fronts and Jets; Temperature**

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WISTING, OSCAR

Oscar Wisting was Roald Amundsen's most trusted and loyal expeditioner. Together, the two were the first to reach both the South Pole and the North Pole.

Wisting was born in Larvik, southern Norway, on June 6, 1871. He chose the navy as his career, but a meeting with Amundsen in Horten in 1909 partially changed this. Amundsen was testing kites as a possible aerial inspection platform for use in the ice, and he spontaneously invited Wisting to join his next expedition. When Wisting left on what became Amundsen's South Pole expedition, 1910–1912, he left behind a large family. He was more or less away from his family with Amundsen for 16 years, which resulted in bitterness amongst his children and a later bad conscience for him.

Wisting's attributes for the South Pole expedition were his all-round practical sense, endurance, and, not least, his loyalty. Amundsen needed men who obeyed without question. At the winter base Framheim, one of Wisting's jobs was to man the sewing machine in one of the snow caves that extended from the base hut. Here, among other jobs, he resewed the tents to make them lighter and more suitable for the sledge journey. He was one of the four men whom Amundsen chose for the South Pole journey, driving his own dog team. On December 14, 1911, the five men together held the Norwegian flag as it was planted at the Pole.

Wisting's merits on the South Pole expedition impressed Amundsen, who encouraged him afterwards to gain additional expertise for future expeditions. He obtained some training in elementary medicine and dentistry, took a diploma as a tinsmith, completed a cookery course, and studied navigation. In 1913–1914 he was in the group that fetched *Fram* back from South America, and in 1918–1925 he was away on Amundsen's *Maud* expedition. On this expedition Amundsen gave him increasing responsibility. He sledged with Helmer Hanssen on a 6-month journey to the nearest telegraph station and with the scientist H. U. Sverdrup on a long trip around the Chukchi Peninsula. When Amundsen left the expedition, Wisting was given major responsibilities, serving as captain during the last drift in the ice, 1922–1925. During the summer of 1923 he flew with Odd Dahl on what was probably the first flight over the Arctic Basin ice field.

Wisting was only home for a few days before he again was called out by Amundsen, this time to the flight in the dirigible *Norge* over the North Pole, with the job of manning the elevator. On the night of May 11–12, he and Amundsen shook hands as the two first to reach both Poles.

In 1928 he was scheduled to help Amundsen search for Umberto Nobile and his dirigible *Italia*. Fortunately for him, there was no room on the plane to Svalbard, and he thereby avoided disappearing with Amundsen. Wisting led an unsuccessful search expedition for his friend.

Wisting's last years were partially devoted to saving *Fram* for posterity, in a specially constructed museum in Oslo. During work at the museum on December 4, 1936, he had a heart attack and died alone in his cabin from the Antarctic expedition.

SUSAN BARR

See also **Amundsen, Roald; Hanssen, Helmer; Norwegian *(Fram)* Expedition (1910–1912)**

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WOMEN IN ANTARCTIC SCIENCE

From the beginnings of Antarctic research, women scientists longed to participate, the first few finally gaining permission in the late 1950s. They now play a significant role in Antarctic science, in critical long-term monitoring, in new fields, and in international collaborative projects.

Those whose work is mentioned here are principal investigators for Antarctic scientific projects, or have worked long term in Antarctic fields. They come from seventeen nations.

Atmospheric Sciences

Women are not strongly represented in physics. An early woman physicist in the Antarctic was Nadezhda Kazakova, who led the Russian aerological team on five expeditions beginning in 1969. In 1970, Irene Peden studied properties of the lower ionosphere over the polar regions; Gisela Dreschhoff first surveyed the uranium resource potential of Antarctica in 1972, moving on to study cosmic radiation and its relevance to space exploration.

Middle atmosphere dynamics, using ground-based remote sensing, is a major interest of Susan Avery, former director of the University of Colorado Cooperative Institute for Research in Environmental Sciences (CIRES) and now Executive Vice Chancellor and Provost of the University of Colorado at Boulder. Her research encompassed mesospheric studies using a meteor echo detection and collection system, nonmigrating tides, coupling in the atmosphere through gravity waves, precipitation structure using wind profilers, and development of meteor radar systems. Pene Greet has also conducted long-term studies of the mesosphere. Her work on the design, calibration, operation, and analysis of Fabry-Pérot Spectrometer data, used to study atmospheric motions and temperature, has led to a significant series of observations, particularly on tidal variations. Elizabeth Essex studied the ionosphere, using techniques based on detecting signals transmitted from satellites. Kaoru Sato investigates the dynamics of the atmosphere, including wave dynamics, wave-mean flow interaction, instability, and the ozone hole.

Susan Solomon found key evidence of ozone destruction. An atmospheric chemist, she led the 1986 emergency expedition to investigate the formation of the ozone hole over Antarctica. She made some of the first measurements there that suggested chlorofluorocarbons as the cause of the ozone hole. In 2000 she received the National Medal of Science, the United

States's highest scientific honour, for "key insights in explaining the cause of the Antarctic ozone hole," among other honours and awards.

Anna Jones is another atmospheric chemist. Following the discovery that the chemistry of the polar boundary layer, where snow meets the atmosphere, is much more complex than previously thought, she organized and ran a major year-round measurement project during 2004 (Chemistry of the Antarctic Boundary Layer and the Interface with Snow [CHABLIS]). Involving research groups from six UK universities, this was the largest, longest, and most detailed measurement program of its kind yet carried out in Antarctica.

Irina Repina (Institute of Atmospheric Physics, Russian Academy of Science) has led several studies of Earth–atmosphere interactions.

Geosciences

Climate studies are significant in glaciology. Elisabeth Schlosser, a member of the all-women wintering team at Georg von Neumayer station in 1990, is a glaciologist–meteorologist working on snow accumulation. She uses long-term stable oxygen isotope data from ice cores to investigate past climate.

Recent climate history has been investigated by Elisabeth Isaksson, working since 1996 with the European Project for Ice Coring in Antarctica (EPICA). The last 10–100 years are the focus of Wendy Lawson's research into the response of ice masses to changing climatic inputs. Barbara Smith and Kumiko Azuma conduct studies of climate based on chemical analysis of ice cores, and Nelia Dunbar specializes in the volcanic ash record in Antarctic ice cores and the climate record of the West Antarctic ice sheet. The long-term ice-core work of multiple-award-winning Ellen Mosley Thompson is used in reconstructing the impact of climate on past environmental systems. She provided compelling evidence for contemporary global warming.

Ice mass balance and the dynamics of ice shelves and glaciers contribute to the study of climate change. Elizabeth Morris began her career with studies of the dynamics of ice shelves, moved on to study mass balance, and then became interested in providing ground data to validate and complement satellite data. She has developed an automatic, field-friendly version of the neutron probe for snow-density profiling. Another senior scientist who began studying snow and ice mass balance in 1978, is Julie Palais, now Antarctic Glaciology Program Manager at the US National Science Foundation (NSF). Brenda Hall is investigating the causes of ice ages through studies of the stability of ice sheets, especially the West Antarctic Ice Sheet, and the fluctuations of high-level lakes in the Dry Valleys. Cecilie Rolstad also works on glacier dynamics.

Basic sea-ice studies reveal its formation and thickness, biological significance, and role in climate change. Victoria Lytle, Kim Morris, and Pat Langhorne work in this field. Mary Albert (chair, US Committee to the International Polar Year) has been involved with the US International Trans-Antarctic Science Expedition (ITASE), analyzing firn cores for information on snow structure and air–snow transfer.

In geology, Lois Jones led a four-woman team in 1969 working on the origins of the saline lakes of the Dry Valleys. In 1971–1972 Elizabeth Truswell participated in the Deep Sea Drilling Project voyage to determine when the present ice sheet began to form. The research showed that the ice sheet was dramatically older than previously thought. Truswell works on fossil pollen preserved in off-shore sediments to unravel the nature and history of the early forests and how they were transformed with increasing cold. Focusing on understanding past climate change, paleobotanist Jane Francis investigates fossil woods and their use as tools for climate interpretation. Other Antarctic fossil studies are conducted by Edith Taylor (flora evolution and the use of fossil tree rings as proxy climate records) and Molly Miller (reconstructing benthic communities of freshwater ecosystems of the Phanerozoic period).

Margaret Bradshaw began Antarctic work in 1975, working primarily on rocks and fossils of the Devonian age in sedimentary rocks. Rosemary Askin's early Antarctic studies investigated the breakup of Gondwana. She now studies responses of land vegetation and phytoplankton to environmental and climatic changes and the causes of these changes. Vera Markgraf concentrates on climate change during times of transition, such as the late glacial. Subglacial bedrock is the subject of Terry Wilson's and Robin Bell's research. Bell participates in the investigation of subglacial Lake Vostok.

In structural geology, women are working on plate tectonics and plate boundaries (Joann Stock, Anne Trehu), seismic monitoring (Estella Weigelt, another member of the 1990 all-female German team), and the study of the Earth's magnetic field. This has led Carol Raymond from marine geophysics to the Jet Propulsion Laboratory and the Dawn mission to Mars. Ursula Marvin, now retired, also moved to space research, including the geological mapping of Ganymede, after field studies collecting meteorites in Antarctica (1978–1979, 1981–1982). She chaired the committee that allocates Antarctic meteorite samples to laboratories internationally.

Another geological pioneer is Janet Thomson. Following four reconnaissance expeditions, she compiled and published maps as a British Antarctic Survey mapping geologist, establishing and managing the BAS Mapping and Geographic Information Centre (MAGIC), 1989–2002. She considers her overriding achievement encouraging people to collaborate on projects leading to publications.

Marie Klenova was a pioneering female Antarctic oceanographer (1955), followed by Monica Grasselli and Lilja Ventajas (1979–1980). Now, Gisele Uenzelmann-Neben reconstructs depositional conditions and oceanic current systems from sedimentary structures, and Amy Leventer is chief scientist for the Coring Holocene Antarctic Ocean Sediments (CHAOS) study to develop a climate and oceanographic record for the Quaternary period. Janet Sprintall currently studies the seasonal variability and long-term change of the upper ocean structure of the Drake Passage.

Life Sciences

The ecology and physiology of marine organisms in the Southern Ocean have been studied by women since their first inclusion on marine science voyages (1959: Isobel Bennett and Hope Macpherson; 1962: Mary Alice McWhinnie; 1968–1969: Irene Bernesconi, Adela Caria, Elena Martínez Fonte, and Carmen Pujals). McWhinnie became a world expert on krill *(Euphausia superba)*. Monica Montu, leader of the second Brazilian Antarctic research expedition (1984), also studied krill, and Robin Ross (US) has just completed her twenty-fourth season in Antarctica studying the ecological physiology of zooplankton. She examines trends and cycles in the Antarctic food web, where krill, her special field, is the key species. Bettina Meyer manages a krill group, the work of which is embedded in the international Southern Ocean-Global Ocean Ecosystem Dynamic (SO-GLOBEC) program.

Greta Fryxell and Maria Vernet have specialised in phytoplankton ecology and physiology, and Corina Bruissaard examines phytoplankton viral ecology. Fiona Scott, a phytoplankton ecologist, currently focuses on marine protists. Salps, a very different planktonic grazer, are the subject of Laurence Madin and Patricia Kremer's collaboration. Mary Sewell works on meroplankton, the larval stages of marine invertebrates and fish, now part of the Latitudinal Gradient Project at Cape Hallett. Vonda Cummings, Stacy Kim, and Kathy Conlan all investigate biodiversity on the Antarctic sea floor.

Nadine Johnston (BAS) works with cephalopods. Antarctic fish studies by women began in the 1970s when Yuan Lin DeVries and Audrey Haschemeyer worked on fish antifreeze. Today, both field and laboratory studies of fish are being undertaken by Edith Fanta, head of the Science Committee of the Council for the Conservation of Antarctic Marine Living Resources (CCAMLR), and colleague Lucélia Donatti.

Margaret Clayton has made a long-term study of the reproductive biology of Antarctic macroalgae. In 2003 she conducted the most comprehensive study for nearly 100 years of Falkland Islands seaweeds. A student of Carmen Pujals, Liliana Quartino works on the ecology of Antarctic marine macroalgae. Colleague Gabriele Tosonotto is another marine biologist; María Eliana Ramírez specializes in Antarctic marine benthic flora, and Anne-Marie Schwarz studies plants in both marine and freshwater Antarctic aquatic systems.

The Southern Ocean is subject to intensive study today, especially investigations of the implications of climate change for living organisms. Margaret Clayton, Loes Gerringa, Liliana Quartino, Maria van Leeuwe, and Irene Schloss all work on aspects of ultraviolet B effects on ocean communities. Maria van Leeuwe and Anita Buma are doing pioneering work on iron–biota interactions, and oxidative stress on phytoplankton from solar ultraviolet radiation. Angelika Brandt is involved in scientific planning of the Antarctic Benthic Deep-Sea Biodiversity (ANDEEP): "colonisation history and recent community patterns" expeditions and coordinates biological sciences within the Antarctic Research Program of the German Science Foundation.

Antarctic freshwater aquatic systems have attracted some high-level female scientists. Johanna Laybourn-Parry has 16 years of Antarctic experience. Her projects have focused on carbon cycling in freshwater and saline lakes. Currently she works on bacterial and molecular diversity and the role of viruses in the Vestfold Hills saline lakes. Eleanor Bell also works in this field. Another limnologist, Diane McKnight, investigates the interactions between hydrological, chemical, and biological processes in controlling the dynamics of aquatic ecosystems, and is coprincipal investigator in the McMurdo Dry Valleys Long-Term Ecological Research. Gabriela Mataloni works with a group on the taxonomy and ecology of algae from Antarctic continental environments. Her current project is on the diversity and ecology of maritime Antarctic soil microalgal communities. Another experienced researcher, Kerrie

Swadling, has studied the ecology and biogeography of sea ice–associated organisms, while her lacustrine research centers on using faunal microfossils in the sediment record to describe the Holocene evolution of Antarctic lakes and their environs. Vivian Montecino has examined primary production in Antarctic lakes. The paleo-environment of the testate amoeba fauna of the late Holocene, reconstructed through peat core analysis, is Sofie Vincke's current project. Penny Greenslade has made extensive studies of invertebrate distribution and ecology, especially invasive introduced species.

Basic work on Southern Ocean sea birds began in the 1960s with Nelly Lafuente, Wanda Quilhot, and Christine Muller-Schwarze, and continued with Jeni Bassett in the 1970s. Long-term work on giant petrels is done by Donna Patterson. Rosemary Gales has worked on a range of species of marine birds and mammals, including penguins, albatrosses, and seals. Her research into the ecophysiology and foraging ecology of these species has been directed towards an understanding of their role in the marine environment and their interactions with fisheries and fishing operations.

The Adélie penguin is a biological indicator of Antarctic, especially krill-based, ecosystems. Scientists working on various Adélie programs include Judy Clarke, Silvia Olmastroni, Akiko Kato, Kerry Barton, and Gabrielle Nevitt. Barbara Wienecke and Akiko Kato have worked on emperor penguins.

Tracey Rogers has led programs for 15 years on the life history and population ecology of the leopard seal. As it is an apex predator, changes in its populations reflect changes within the ecosystem. Pam Yochem and Terrie Williams also monitor seal populations and behavior, and Deborah Thiele monitors whale populations.

In botany, two books by Vera Danilovna Aleksandrova are considered "musts" for students of cooler-region plant geography. In basic research, Marina Dorozhkina has worked for several summers investigating the composition of microflora (pollen and spores). The role of Antarctic yeasts in the accumulation and mobilisation of nutrients in polar desert food webs is Laurie Connell's long-term study.

The responses to environmental stress of plants as well as fauna are integral to the study of the impact of climate change. Botanist Sharon Robinson leads a group working from the molecular to the ecological levels. Aspects of this ecosystem interest are shared with Mary Skotnicki, and work on vegetation monitoring using remote sensing also involves Cath Lovelock. Following her earlier multidisciplinary work on the origins and evolution of six endemic, isolated sub-Antarctic island plant species, plant ecophysiologist Françoise Hennion is now investigating the effects of temperature variations on early plant growth.

The ecosystem and biodiversity are of major concern to terrestrial biologists. Patricia Selkirk is an outstanding leader here. Her Australian Antarctic Medal citation in 2004 noted that in more than 25 years of Antarctic service she has produced a substantial and influential body of work in the field of Antarctic and sub-Antarctic science, has acted as a pioneer and role model for women scientists in Antarctica, and has strongly advocated Antarctic science. A multidisciplinary scientist, her research has been broad ranging, from landscape-level geomorphology and vegetation history through to organism-level studies of plant reproduction and subcellular genetics. This research has formed much of the foundation for sub-Antarctic plant biology. She was part of the team that first discovered plant viruses in the sub-Antarctic and was the first researcher to value the sub-Antarctic region as the outer edge of the Antarctic Zone in monitoring climate change.

Dana Bergstrom, once Dr. Selkirk's graduate student, is chief officer for the SCAR Program Group on Regional Sensitivity to Climate Change (RiSCC) in the sub-Antarctic, has undertaken a vegetation history of Macquarie Island, and has worked on most sub-Antarctic Islands. Sieglinde Ott investigates developmental biological adaptations of maritime Antarctic lichens, the genetic diversity of lichen symbiotics, and Antarctic nunataks as model ecosystems. A spatial ecologist, Melodie McGeoch works on the quantification of the spatial variation across Marion Island of the keystone plant species *Azorella selago,* towards understanding the likely impacts of climate change on the system. Amanda Slager-Bastos is studying the genetic characterization of sub-Antarctic island fauna, and their biodiversity.

Soil biodiversity is Diana Walls's field, assessing the importance of this diversity to ecosystems. She has studied the impact of global change on soil species in the Antarctic Dry Valleys, with a major focus on the many ecosystem processes that are mediated by soil organisms.

Human Impacts

Conservation of the Antarctic is an obligation for Antarctic Treaty Members and often requires research to determine the best approach. One major concern is the cleanup of oil spills. Elizabeth Kerry's pioneering work demonstrated that it was possible to enhance the activity of oil-degrading organisms and therefore increase the rate of breakdown of oil spills in the Antarctic by the addition of fertilizer solutions to oil-contaminated soils. This procedure (bioremediation) has been investigated further as part of a major Australian program at Casey, established to determine the best way to clean up the Thala tip. Many women were and still are involved in this work.

Jackie Aislabie leads an interdisciplinary team to support environmental protection and management of ice-free areas of the Ross Sea region. She investigates the effects of hydrocarbon spills on Antarctic soils and is currently determining how to manipulate soil conditions to maximise hydrocarbon degradation. Other team members include Roberta Farrell, working on microbial biodiversity; Julia Foght, on enrichment of hydrocarbon-degrading bacteria with potential for bioremediation of spill sites; Megan Balks, on the impacts of human activities on soil environments; and Emma Waterhouse, on environmental management practices.

Another aspect of conservation is the identification of organisms present as a result of human activity, with a view to adapting management practices to reduce such introductions. Elizabeth Kerry identified fungal species in Antarctic soils in station areas, but not in natural ecosystems, considered likely to have been introduced via human activities.

Studies of sea-bed disturbance, especially the effects on crustacean communities of chemical toxins, are Kathy Conlan's work, and Sabine Duquesne has investigated ocean toxins. Simonetta Corsolini studies the bioaccumulation and toxicity risk assessment of persistent organic pollutants, and their distribution along the food webs. The response to stress of marine organisms is Doris Abele's main field, and she is organising an interdisciplinary exploration of the effect of the recent rapid warming at the western Antarctic Peninsula on terrestrial and marine coastal ecosystems. The effects of ultraviolet-induced damage on marine organisms have been Deneb Karentz's long-standing work, now applied to the ecological implications of Antarctic ozone depletion.

Emma Waterhouse works in the development and implementation of environmental management practices for Antarctic operations and edited a groundbreaking publication on Ross Sea environmental management. Jennie Whinam considers the highlight of 18 years of sub-Antarctic research to be the use of the results from their alien species project to fundamentally change the way that quarantine is viewed institutionally and in practice. Penny Greenslade, an entomologist, has also contributed to Australian quarantine and management practices.

The impact of tourism is of increasing concern in the Antarctic. Rosamunde Codling's 1980s research on the development and evaluation of tourism is considered seminal. Debra Enzenbacher undertook the first doctoral dissertation on Antarctic tourism policy. Melissa Giese's work on the impact of human activities on Antarctic wildlife has had policy implications.

Conservation

Lyn Goldsworthy, Janet Dalziell, Sabine Schmidt, and Liz Carr, all qualified scientists, have undertaken Antarctic conservation work through Greenpeace, including station monitoring and advocacy for the "World Park" proposal.

Archaeologists Estelle Lazer, Karen Townrow, and Angela McGowan have worked in projects to determine and preserve significant Antarctic historic sites. Janet Hughes investigated corrosion in Mawson's huts, while Roberta Farrell has studied microbial diversity and degradative fungi active in Scott's huts. Norwegian sites were surveyed by Susan Barr.

In cutting-edge research, Rosamunde Codling (UK) sought to define Antarctic "wilderness and aesthetic values," a concept enshrined in the Protocol on Environmental Protection to the Antarctic Treaty. She suggested methodologies for their identification and assessment, basic principles for assessment for area protection and management, and appropriate survey techniques.

One of the major focuses on research in the near future is the 2007–2009 International Polar Year, which will involve new multidisciplinary and collaborative work. Women are playing key roles in this Antarctic science and in related policymaking.

ROBIN BURNS

See also **Antarctic Ice Sheet: Definitions and Description; Atmospheric Boundary Layer; Climate Change; Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Dry Valleys; Fish: Overview; Flowering Plants; Fossils, Plant; Glacial Geology; Greenpeace; Ice Shelves; International Polar Years; Ionosphere; Isotopes in Ice; Lake Vostok; Lichens; Marine Biology: History and Evolution; Meteorites; Meteorological Observing; Oases; Ozone and the Polar Stratosphere; Penguins: Overview; Phytoplankton; Plate Tectonics; Polar Desert; Polar Mesosphere; Pollution; Protocol on Environmental Protection to the Antarctic Treaty; Sea Ice: Types and Formation; Seabirds at Sea; Seals: Overview; Soils; Snow Chemistry; Streams and Lakes; Subglacial Lakes; Tourism; Vegetation; Volcanic Events; Whales: Overview; Zooplankton and Krill**

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WOMEN IN ANTARCTICA: FROM COMPANIONS TO PROFESSIONALS

Antarctica attracts both women and men. Women have played important roles as supportive wives (e.g., Kathleen Scott and Paquita Mawson); as expedition fund-raisers and publicists (e.g., Dorothy Irving-Bell); as historians of expeditions (e.g., Ann Savours [UK], Gracie Delépine [France], and Helen Wright [US]); as curators of samples collected (e.g., Helen Bargmann [UK]), and in the development of the institutions and services central to the national Antarctic operations today. The Australian National Antarctic Research Expeditions (ANARE) were the first to include key female support staff on resupply voyages to Macquarie Island (scientific secretaries Susan Ingham, biologist, 1959; Ena Thomas, geographer, 1963–1964; and Elizabeth Chipman, 1967; Jutta Hösel, photographer, 1968; and the first female Antarctic journalist, Kirsten Ward, 1961–1962).

Female Companions

Women did accompany men to the far south on exploratory voyages and whalers' and sealers' ships (Chipman 1986). French woman Jeanne Baré (Baret) is the first one recorded, aboard Bougainville's Falkland Islands expedition in 1766–1777. As botanist/

valet, she was the first woman with a professional role in Antarctica. She was followed by country-woman Louise Séguin (Louison), a stowaway on board *Le Roland* on its 1773–1774 voyage to the Îles Kerguelen.

Some were captains' and officers' wives (Rose de Freycinet [France], aboard *Uranie,* 1817–1820; several Australian, American, and British women from 1842 onwards). The first woman accompanying a combined exploratory/whaling voyage was Norwegian Ingrid Christensen, the captain's wife, in 1927–1928. In 1931 she and Mathilde Wegger were aboard *Thorshavn* when it sighted the Antarctic continent, another first. Then in 1935 Captain Klarius Mikkelsen's Danish-born wife Caroline became the first woman to set foot on the Antarctic continent, near today's Davis station.

From the early 1800s women were present on the settlements on the sub-Antarctic islands. The first recorded marriage, birth, and death of females in the far south were in 1850 on the Auckland Islands. In 1890 Henry Charles Mellish managed the sealing gang on Macquarie Island, accompanied by his wife, who acted as cook; there was a New Zealand woman on her husband's whaling base on Campbell Island in 1911, and in 1913–1914 Klara Olette Jacobsen, from Norway, lived with her husband on South Georgia and gave birth to their daughter Solveig there.

Andrée Aubert de la Rüe accompanied her geologist husband on a private expedition to Îles Kerguelen in 1928–1929, the first of four summers and a winter (1952) for the couple. From 1944, women from France, the UK, and Norway came to Îles Kerguelen and South Georgia, as officials' or scientists' wives, and in 1953–1954 an American woman, Eleanor Rice Pettingill, summered with her ornithologist husband on the Falkland Islands. The first woman in the sub-Antarctic in her own right was G. L. Hammond, a New Zealand medical theatre sister on Campbell Island for the 1945–1946 summer.

In 1947 Finn Ronne led a private expedition to the Antarctic. Among the twenty-three members were his wife Edith (Jackie), who undertook recording duties, and a recently wed couple, Jennie and Harry Darlington. They were based at Stonington Island off the Antarctic Peninsula. Edith and Jennie, both in their twenties, were the first women to winter in the Antarctic.

During the 1947–1948 summer, Rosa Markmann de Gonzalez Videla and her daughters Rosa and Silvia, the family of the Chilean President, and Elena Cerda de Bulnes, whose husband was part of the presidential party, visited the South Shetland Islands and the Antarctic Peninsula. A second Chilean first lady visited in the 1968–1969 summer (Maria Ruiz-Tagle de Frei Montalva, along with her daughter, and with female journalist Carmen Marinoa de Ginesto), while another Chilean president's wife visited in 1976–1977 (Lucia Hirfiart de Pinochet).

Over a century after women began to accompany men to sub-Antarctic settlements, six women and their children joined the Argentine army base at Esperanza. The probable first marriage on the continent took place there during the 1978 winter.

Women in the Era of Antarctic Science

A new stage in Antarctic exploration began in 1947, with the establishment of national bases primarily for scientific work. Eight years later women began to travel south to undertake their own scientific work. For many, it was both the fulfillment of a dream and a very hard struggle to gain acceptance for Antarctic service. Sir Vivian Fuchs, then Director of the British Antarctic Survey, thought women could not handle the heavy cases of supplies and would require new facilities. Further, "their presence would change the whole psychological atmosphere of the bases" (Brisbane *Courier Mail,* July 12,1963). More bluntly, the US Commander of Operation Deepfreeze, Admiral Dufek, thought women would "wreck the illusion of being frontiersmen going into a new land and the illusion of being a hero" (*Sydney Morning Herald,* May 3, 1959). Such objections persisted even after women were included in official national expeditions. The facilities proved no barrier, since as one woman succinctly stated, "a lock for the toilet doors sufficed," but some doubts about their physical strength and many about their potentially disruptive social and psychological influence persisted well into the 1980s and even 1990s.

The desires to seek adventure, to test oneself in difficult conditions, to experience a small isolated community, and to work in this pristine land are shared by men *and* women, and some women were determined to break into Antarctic work. They repeatedly applied for advertised vacancies, and lobbied officials; they asked why they were rejected, did extra courses, and sought additional experience until it became very difficult to refuse their applications. They were highly selected and faced extra hurdles, such as a trial summer for the first Australian female continental station leader. And for several decades many women reported opposition from some male expeditioners. Women are now included in most national programs, though they still do not constitute half the station personnel even in summer, partly reflecting their underrepresentation in the professions in Antarctica and in senior positions in science.

At first women were ship based. Eminent professor and member of the Council for Antarctic Research of the USSR Academy of Sciences Maria V. Klenova, a marine geologist, was the first, working aboard the Russian vessels *Ob'* and *Lena* and at Mirnyy base, in the summer of 1955–1956. The expedition undertook mapping of uncharted areas of the Antarctic coastline, and her work contributed to the first Antarctic atlas. V. S. Korotkevich, hydrobiologist, and L. M. Nikolaeva were aboard *Ob'* the following summer, Korotkevich returning in 1962–1963. From then onwards Russian women also worked as ship's crew members.

Four women travelled to Macquarie Island with ANARE in December 1959 (Isobel Bennett, marine biologist; Mary Gilham, UK botanist; Susan Ingham, biological secretary; and Hope Macpherson, intertidal ecologist). Bennett and Macpherson returned the following summer, together with Ann Savours (historian, UK) and Elise Wollaston (botanist). Based on *Thala Dan,* under charter to the Australian program, Danish radio officer Inger Knudsen made her first visit to the continent in 1967–1968, the first female ship's officer.

Two French women spent the 1961–1962 summer on Îles Kerguelen: geophysicist Jeanne Baguette and an engineer specialising in the ionosphere, Dr. Genéviève Pillet, the latter returning in 1964–1965 and 1967–1968. In 1962–1963, another French engineer, Christiane Gillet, spent the first of many summers in Antarctica. As head of the technical bureau of the Expéditions Polaires Français, she has been responsible for provision and maintenance of technical equipment and machinery for the science programs at the stations. Journalist Yvonne Rebeyrol went south for the 1964–1965 season.

Four female American scientists were on board the USNS *Eltanin* for the first time in 1962–1963: Dr. Mary Alice McWhinnie, an established biologist, and Phyllis Marcinak, E. Figetti, and F. D. Frelen. After spending five more seasons in the south, in 1974 McWhinnie and Sister Mary Odile Cahoon became the first female scientists to winter on the continent. As chief scientist at McMurdo Station, McWhinnie was also the first woman in charge of that station.

In 1968–1969, four experienced Argentine scientists—Professors Irene Bernasconi (marine biologist), Adela Caria (microbiologist), Elena Martínez Fonte (marine biologist), and Carmen Pujals (botanist)—spent the summer conducting research on the continent.

Six women visited the South Pole for the first time in November 1969, linking hands to step off the plane together. Five were scientists, including New Zealanders Eileen McSaveney and Pam Young and Americans Lois Jones (first female scientific team leader), Kay Lindsay, and Terry Tickhill, plus journalist Jean Pearson. Finally, in 1979, medical doctor Michele Raney became the first woman to winter at Amundsen-Scott South Pole Station.

The first female summer scientist at McMurdo Station was psychologist Christine Muller-Schwarze, observing penguin behavior. Arriving just before Jones' team, she declined the brief South Pole trip. The following year two women worked at remote Byrd Station: electrical engineer Irene Peden, and field assistant Julia Vickers (New Zealand). In 1973, Lieutenant Ann E. Coyer became the first American woman to report for Antarctic duty with the US Navy. Female support staff Elena Ann Marty and Janet L. Boyd were included the next year. Twenty years later Trina Baldwin became the first woman to serve as wintering officer-in-charge at McMurdo Station.

Biologist Maria Darby and journalist Dorothy Braxton were the first New Zealand women to visit the Antarctic continent, on a tourist ship (1967–1968). Pam Young followed in 1969–1970 as a field assistant. The first New Zealand woman to undertake her own program was geologist Rosemary Askin, 21 years old when she arrived in Victoria Land in 1970. She continues her Antarctic work today, as does fellow New Zealand geologist Margaret Bradshaw, whose first season was in 1975–1976. Ann Chapman, biologist, and Barbara Spurr, limnologist, also began their research in the Antarctic in 1975–1976. Thelma Rodgers was the first technician at Scott Base in 1976–1977 and the first New Zealand wintering woman in 1979.

The first three Australian women to visit the continent were Elizabeth Chipman (information officer), Jutta Hösel (official photographer), and Shelagh Robinson (welfare officer), in 1975–1976. With them was British doctor Zoë Gardner, first woman to winter on an Australian station (1976, Macquarie Island). The first Australian woman to spend a full summer on the continent was Jeannie Ledingham (Cape Denison, 1977–1978), while in 1981 Louise Holliday, a medical doctor, was the first woman to winter at an Australian continental station (Davis). The first Australian female scientist to conduct a land-based scientific program on the Antarctic continent was biologist Elizabeth Kerry, in 1978–1979. She travelled to many locations around and remote from Casey station, collecting soil, moss, and lichen samples to isolate and identify fungi, as part of her study of the natural fungal flora of Antarctica.

Women soon occupied other positions with ANARE. Sarah Stephens was radio officer in 1977 at Macquarie Island; the next year Enid Borschmann wintered there as chef, and in 1983 Gay Woolley became the first female meteorology observer. The first female station leaders served in 1989: Alison Clifton at Macquarie Island and Diana Patterson at Mawson. Joan Russell followed (1990, Casey), then Louise Crossley (1991, Mawson). Crossley also led the summer Prince Charles Mountains field expedition in 1992. Meteorology observer Denise Allen was the first woman to winter at each of the Australian stations.

Other notable firsts for women include the all-female wintering team of nine at the German station Georg von Neumayer in 1990–1991 under the leadership of Monika Puskeppeleit (mixed wintering teams were allowed from 1995–1996). In 1987–1988 Heather Adamson conducted research at Casey; her daughter Erica was expedition biologist, staying over winter and the following summer. And in 1989–1990 Patricia Selkirk and daughter Jennifer pursued separate projects on Macquarie Island. The first wintering South African women were biologists Marianna Steenkamp and Marieta Cawood at Marion Island in 1987–1988.

By 1992 women were members of wintering teams for Argentina, Australia, New Zealand, Russia, the UK, and the United States, and in that year botanist Maria Agata Olech was base leader for the Polish station Arçtowski. Brazilian women were also taking leadership roles. The first black South African woman to be principal investigator for an Antarctic project was Law Professor Loretta Feris (2005–2006 season).

International cooperation is an integral part of the management of Antarctica, and women have been included in the expeditions of other nations, sometimes well ahead of permission to join their own national operations, or in lieu of national ones. Thus, in 1976–1977 British geologist Janet Thomson, the first British female scientist to undertake Antarctic fieldwork, joined an American expedition.

Women now play key roles in the management of national Antarctic programs. Gillian Wratt was director of the New Zealand Antarctic Programme from 1992–1996. From 1996 to 2002 she was chief executive of the newly created New Zealand Antarctic Institute (Antarctica New Zealand). Other positions she has held include chair of the Council of Managers of National Antarctic Programmes (COMNAP), 1998–2001; vice chair of the Antarctic Treaty Committee on Environmental Protection, 1998–2001; and chair of the Cape Roberts Project Operations Management Group, 1993–2002. Margaret Lanyon had a 36-year career as manager of the US New Zealand Antarctic Operations. For 15 of her 20 years with the British Antarctic Survey (BAS), Linda Capper has been head of press, publicity, and education. Carol Jacobs has been assistant director (liaison and administrative services) since 1995 with the South African National Antarctic Programme (SANAP) and the Prince Edward Islands Management Committee (PEIMC).

Women are now country members and observers on the three major scientific groups of the international Scientific Committee on Antarctic Research (SCAR). They serve as experts on Antarctic science selection panels, and three of the six Antarctic science program directors at the US National Science Foundation are currently women: Marie Bundy, Julie Palais, and Polly Penhale.

Honors for Women's Antarctic Service

Women have received UK awards for polar service. In 1986, Virginia Fiennes became the first woman to be awarded the Polar Medal, for her part in the Transglobe Expedition. New Zealand geologist Margaret Bradshaw received a Polar Medal in 1993, Jane Francis (a paleoclimatologist) received one in 2002, and Elizabeth Morris (a glaciologist) received one in 2003. An Order of the British Empire (OBE) was awarded to Morris in 2002, and a Member of the British Empire (MBE) to Linda Capper of BAS in 2003. Bradshaw has also received the Royal Society of New Zealand Science & Technology Medal in 1994.

Norwegian glaciologist Monica Kristensen-Solås received the Founder's Gold Medal of the Royal Geographical Society in 1989 as originator and leader of the 1986–1987 "90 Degrees South Antarctic Expedition." This expedition commemorated the seventy-fifth anniversary of Roald Amundsen's attainment of the South Pole. Using dogs, like Amundsen, Kristensen's party was 400 km short of the South Pole when forced to turn back to rendezvous with the ship, a hazard for many Antarctic expeditions.

BAS makes two awards. The Fuchs medal, in recognition of outstanding devotion to the Survey's interests and beyond the call of duty, has been received by Eleanor Honnywill (1975), Anne Todd (1987), Myriam Booth (1989), Janet Thomson (2001), and Alex Gaffikin (2001). The BAS Club Laws Prize for a young polar scientist was won in 2000 by Anna Jones.

The Australian Antarctic Medal has been awarded to six women: Denise Allen (1989, meteorological observer and deputy station leader); Lynn Williams (1989, medical officer, researcher, and field leader); Meredy Zwar (1995, outstanding chef and expeditioner); Judith Clarke (1996, veterinary biologist); Madeleine Wilcock (2000, doctor, for an emergency rescue), and Patricia Selkirk (2004, terrestrial biologist and mentor of many younger scientists).

Women have also been recognized in the awards of other nations.

Adventurers

Nancy Griffith was one of the crew of six aboard the yacht *Awahnee* that circumnavigated the Antarctic in 1971. Two private ventures in 1977–1978 included women. New Zealander Naomi James sailed to the Falkland Islands on the *Crusader,* and Australian-born Sally Poncet made her first venture south, with French husband Jérôme, aboard *Damien II*. The Poncets have subsequently wintered on the continent, settled in the Falklands with their three sons, and spend six months of each year studying bird populations on the islands surrounding Antarctica.

Virginia Fiennes was not only a key inspiration for her husband's 1979–1982 Transglobe Expedition, she was the radio operator, wintering at Ryvingen in Dronning Maud Land. She also designed the huts for the base camp. Jill McNicol was the cook for the sea portion of the expedition, and New Zealander Jeni Bassett was on board as seabird and mammal observer.

The Oceanic Research Foundation (ORF) undertook its first Antarctic expedition in 1977–1978 with Australian mountaineer Dorothy Smith aboard. Elizabeth Kerry, already a veteran of three summers on Macquarie Island, studied soil samples with that expedition. Smith participated in the second ORF venture in 1981–1982, a joint Australia–New Zealand expedition to Douglas Mawson's old base at Cape Denison that included Jeni Bassett, Margaret Huenerbein, Karen Keys, and Barbara Muhvich. An international group under the auspices of ORF froze their ship in for the 1983 winter. Mimi George, an American psychologist and deputy leader, studied reactions to the extreme conditions. British geographer Gillian Cracknell was also there. Pauline English and Meg Thornton were on William Blunt's 1983 expedition to Heard Island, where they both successfully climbed Big Ben, Australia's highest mountain. Thornton again visited Heard Island in 1984–1985. Blunt subsequently became involved with Project Blizzard, the attempt to restore Mawson's historic huts, which involved Julie Johnston and Estelle Lazer in 1984–1985, Angela McGowan in 1985–1986, and Lazer again in 1986–1987.

Further private visits have taken place since 1981–1982, often husband–wife couples, with women from Australia, France, Germany, and the United States. Margaret Werner made her first visit in 1988 as a crew member of an Australian Bicentennial team. Australian Brigitte Muir climbed Mt. Vinson Massif in 1991 and became the first woman to climb the highest peak on every continent.

The South Pole has become the goal of overland treks by ski and sail. The first two women to ski there were Americans Victoria Murden and Shirley Metz in 1988–1989, with a mixed team of eleven. An American all-female group reached the Pole in 1992–1993: Ann Bancroft (leader), Sue Giller, Anne Dal Vera, and Sunniva Sorby.

The first female solo, unsupported journey to the South Pole was made in 1994 by Norwegian Liv Arnesen, who covered 1200 km in 50 days. In 2001 she and Ann Bancroft made the first female attempt to cross the entire continent by ski and sail. Insufficient wind prevented them from reaching the opposite coast unaided by a few days. Three years after her solo trek to the South Pole in 1996, French alpinist Laurence de Ferrière left the South Pole to cross virgin territory to the coast at Dumont D'Urville Station. The French Polar Institute insisted on picking her up, 275 km short of her target, due to dangerous weather.

In 2000 five British women walked to the South Pole: Caroline Hamilton, Pom Oliver, Ann Daniels, Rosie Stancer, and Zoe Hudson. Rosie returned alone in 2004, the oldest woman to make it (43) and the second-fastest person. Two other British women walked to the South Pole in 2000: Fiona Thornewill (with husband Mike) and Catherine Hartley. Thornewill also trekked there alone in 2004, arriving 3 days ahead of Stancer.

Robin Burns

See also **Adventurers, Modern; Amundsen, Roald; Amundsen-Scott Station; Antarctic Peninsula; Argentina: Antarctic Program; Auckland Islands; British Antarctic Survey; Campbell Islands; Christensen Antarctic Expeditions (1927–1937); France: Antarctic Program; Heard Island and McDonald Islands; Kerguelen Islands (Îles Kerguelen); Macquarie Island; McMurdo Station; Mawson, Douglas; New Zealand: Antarctic Program; Protocol on Environmental Protection to the Antarctic Treaty; Ronne Antarctic Research Expedition (1947–1948); Russia: Antarctic Program; Scientific Committee on Antarctic Research (SCAR); South Africa: Antarctic Program; South Georgia; South Pole; South Shetland Islands; Tourism**

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WORDIE, JAMES

Sir James Mann Wordie was the elder statesman of polar exploration, whose 45-year career as explorer and academic linked the Heroic Age of Antarctic exploration with the mechanised and scientific era. He participated in nine polar expeditions, pioneered the concept of "summer expeditions," and greatly influenced a new generation of explorers.

Wordie was born in Glasgow on April 26, 1889, the youngest son of wealthy businessman John Wordie and his wife Jane (née Mann). He excelled as a student, first at the Glasgow Academy, then graduated from Glasgow University in 1910 with an honours degree in geology and attended St. John's College, Cambridge, as an advanced geology student.

Wordie met Raymond Priestley and Frank Debenham, veterans of Robert Falcon Scott's *Terra Nova* expedition (1910–1913), at Cambridge and volunteered to join Ernest Shackleton's Imperial Trans-Antarctic Expedition (1914–1917) as geologist. He was marooned on Elephant Island for four and a half months in 1916 and appointed chief of scientific staff on his return to the UK with responsibility for the publication of the expedition's official papers. Wordie joined the Royal Field Artillery in 1917 and was wounded near Armentieres in 1918.

Wordie travelled on two expeditions to Spitsbergen under William Speirs Bruce (1919 and 1920), and in 1921 ventured to Jan Mayen Island, where he made the first-ever ascent of Mt. Beerenberg. Wordie led five more voyages to the Arctic (East Greenland, 1923, 1926, and 1929; Baffin Bay, 1934; and Greenland and the Canadian Arctic, 1937) and was a mentor to the younger ranks of explorers, including Vivian Fuchs, Gino Watkins, and August Courtauld. He developed the private "university summer expeditions," which helped switch the focus of Arctic journeys from geographic discovery to scientific understanding. For 30 years he advised numerous Antarctic and Arctic expeditions, including the British Graham Land Expedition (1934–1937) and the Norwegian-British-Swedish Antarctic Expedition (1949–1952). By the 1930s, few expeditions left Britain without first consulting Wordie.

Wordie was a formidable administrator and was associated with creating the Scott Polar Research Institute (SPRI) in 1920, and he was chairman of the management committee of the institute for 18 years. He helped develop British policy towards the Antarctic regions, initially as a member of the Discovery Committee for 20 years from 1923. In 1943 he was the head of Operation Tabarin, the Naval Intelligence body responsible for the Antarctic, which later became the Falklands Islands Dependencies Survey (FIDS) and subsequently the British Antarctic Survey (BAS). Wordie was appointed honorary secretary of the Royal Geographical Society (RGS) in 1934 and president of it in 1951. He was vice-chairman of the Everest Committee, which was a major force behind the first successful ascent of Mount Everest. He was a close advisor to Fuchs and vice-chairman of Fuchs's Commonwealth Trans-Antarctic Expedition (1955–1958), which made the first crossing of Antarctica. He was also chairman of the British Mountaineering Council (1953) and chairman of the British National Committee for the International Geophysical Year (1957–1958). During his acclaimed academic career at St. John's College, Cambridge, Wordie was appointed lecturer and tutor of geology, president (1950), and master of the college (1952–1959).

Wordie's honours include the Silver Antarctic Medal (1917); Back Grant, RGS (1920); Bruce Medal, Royal Society of Edinburgh (1926); Founder's Medal, RGS (1933); Order of St. Olav, Norway (1943); Gold Medal, Royal Scottish Geographical Society (1944); Commander of the British Empire (1947); Charles Daly Medal, American Geographical Society (1952); and knighthood for services to polar exploration (1957). He died on January 16, 1962.

Michael Smith

See also **Antarctic Accounts and Bibliographic Materials; British Antarctic Survey; British Graham Land Expedition (1934–1937); Bruce, William Speirs; Commonwealth Trans-Antarctic Expedition (1955–1958); Debenham, Frank; Fuchs, Vivian; Ice Shelves; Imperial**

Trans-Antarctic Expedition (1914–1917); International Geophysical Year; Norwegian-British-Swedish Antarctic Expedition (1949–1952); Priestley, Raymond; Ross Ice Shelf; Scott Polar Research Institute; Shackleton, Ernest; United Kingdom: Antarctic Program

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WORLD CLIMATE RESEARCH PROGRAMME (WCRP)

The World Climate Research Programme (WCRP) was established as a principal component of the World Climate Programme in 1980, with joint sponsorship from the World Meteorological Organization and the International Council for Science (ICSU). The Intergovernmental Oceanographic Commission (IOC) of UNESCO became a sponsor in 1993. WCRP has two major objectives: to determine the extent to which climate can be predicted, and to determine the extent of human influence on climate. A WMO/ICSU/IOC Joint Scientific Committee is responsible for formulating the overall scientific concepts and goals of the WCRP and for organizing the required international coordination of research efforts. The essence of WCRP science is understanding, observation, quantification, prediction, and projection of the climate system on a range of time scales, from intraseasonal through seasonal, yearly, and decadal to centennial. The economic, environmental, and social benefit of such forecasts is already significant and will grow as prediction skill improves.

Whilst WCRP research focuses on the physical system, it is increasingly concerned with the more complete climate system, which includes chemical and ecosystem interactions, and the interactions of human activities with global climate and the environment. Thus, the WCRP has joined with other global environmental programmes (IGBP, IHDP, and DIVERSITAS) to form the Earth System Science Partnership to further the integrated study of the earth system, the changes that are occurring, and the implications for global sustainability.

WCRP currently consists of four broad-based multidisciplinary core projects, all relevant to Antarctica. The Climate Variability and Predictability Project (CLIVAR) (http://www.clivar.org), a follow-on from the World Ocean Circulation Experiment and the Tropical Ocean–Global Atmosphere project, is focussed on climate variability, extending effective predictions of climate variation, and refining the estimates of anthropogenic climate change. CLIVAR is attempting particularly to exploit the "memory" in the slowly changing oceans and their interaction with the atmosphere and cryosphere.

The Climate and Cryosphere (CliC) Project (commenced in 2000) addresses the ice-covered regions of the Earth's surface (including the Antarctic Ice Sheet and the surrounding ice-covered Southern Ocean). CliC aims to assess the impacts of climatic variability and change on the cryosphere and its overall stability and to determine the consequences of such impacts on climate. CliC seeks to enhance monitoring of the cryosphere, to understand climate-related processes, and to model and understand the cryosphere's role in the climate system. Changes to the cryosphere are particularly important to sea-level change.

Climate processes in the Southern Ocean are important globally and are addressed by a combined CLIVAR–CliC–SCAR Southern Ocean Panel.

The Global Energy and Water Cycle Experiment (GEWEX) focuses on variability and potential change to the global hydrological cycle and energy budget processes. The Stratospheric Processes and Their Role in Climate (SPARC) project is concerned with coupling between the stratosphere and the lower atmosphere, including ozone depletion and its impacts.

The development of improved and comprehensive global climate models is an essential unifying theme running through WCRP. Such models are the fundamental tools for understanding and predicting natural climate variations and for providing reliable estimates of anthropogenic climate change. WCRP contributes to the design and implementation of a comprehensive, integrated, and sustained global climate observing system. WCRP also promotes multiyear model reanalyses of the global atmospheric circulation with state-of-the-art assimilation/analysis schemes. There is a growing need for similar reanalyses for the oceans and for special regions such as the Antarctic.

JOHN A. CHURCH and IAN ALLISON

See also **Antarctic Ice Sheet: Definitions and Description; Climate; Climate Change; Earth System,**

Antarctica as Part of; International Geosphere-Biosphere Programme (IGBP); World Meteorological Organization

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WCRP information, including its strategic framework Coordinated Observation and Prediction of the Earth System (COPES). http://www.wmo.int/web/wcrp/wcrp-home.html

WORLD CONSERVATION UNION (IUCN)

History

IUPN, the International Union for the Protection of Nature, was founded in 1948 at a Conference at Fontainebleau, France, convened by the Government of France, UNESCO, and the Ligue Suisse pour la Protection de la Nature. It was planned as a world forum for nature conservation, threatened by postwar change. It became IUCN, the International Union for Conservation of Nature and Natural Resources, in 1956, and in 1990 adopted the descriptive title "The World Conservation Union."

Constitution and Programme

IUCN is a uniquely "hybrid" international organization, its 1036 members (in 2004) including 77 states, 114 government agencies, 77 international nongovernmental organizations (NGOs), and 735 national NGOs, spread across 144 countries. Its sovereign body is the General Assembly of all its members, now styled the World Conservation Congress and held every 4 years. The congress elects the president, treasurer, and council, and the chairs of six voluntary networks called Commissions. These latter are another unique feature linking over ten thousand individual conservationists to address the conservation of species, the protection of national parks and other areas, the management of ecosystems, environmental law, education and communication, and environmental economics and social policy.

The headquarters of IUCN is at Gland, in Switzerland, but the secretariat is decentralized, with thirty-two offices scattered around the world. The main programmes are concerned with ecosystems and their management, sustainable human livelihoods, global change and biodiversity, social policies, and environmental law. Many projects are undertaken in developing countries and in partnership with member organizations. The IUCN produces methodological handbooks, overviews of the status of species (notably the authoritative Red List of Threatened Animals), a United Nations List of National Parks and Protected Areas, and a diversity of action plans. IUCN has led in the production of two World Conservation Strategies (in partnership with the United Nations Environment Programme and the World Wide Fund for Nature) and has worked with many countries to prepare National Conservation Strategies.

IUCN and Antarctica

Each General Assembly or World Conservation Congress adopts resolutions and recommendations, and a number of these have called for action in the Antarctic. In 1960 IUCN urged that the new Antarctic Treaty set aside inviolate areas for the conservation of wildlife and supported SCAR's work on what became the Agreed Measures for the Conservation of Antarctic Fauna and Flora. In 1978 IUCN emphasised the need to conserve krill and other Antarctic marine resources, and in 1980 it participated in the negotiation of CCAMLR, the Convention on the Conservation of Antarctic Marine Living Resources. In 1981 the Union proposed that the Antarctic be specially designated as a protected area. In 1984 and 1988 concern was expressed over waste disposal, the depletion of some fish stocks, the rapid expansion of Antarctic tourism, and the possible exploitation of minerals (something most IUCN members strongly opposed).

IUCN itself published an Antarctic Conservation Strategy in 1991 and has held several joint symposia with SCAR. The union has observer status as an NGO at Antarctic Treaty consultative meetings and strongly supported the negotiation of the Protocol on Environmental Protection to the Antarctic Treaty. Its principal contribution is as the voice of the professional world conservation community, but it is significant that the majority of Antarctic Treaty consultative parties are also state members of IUCN.

Martin Holdgate

See also **Antarctic Treaty System; Conservation of Antarctic Fauna and Flora: Agreed Measures; Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Protocol on Environmental Protection to the Antarctic Treaty; Scientific**

Committee on Antarctic Research (SCAR); Zooplankton and Krill

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WORLD METEOROLOGICAL ORGANIZATION

International cooperation in Antarctic meteorological and related sciences and services is underpinned by the activities of the World Meteorological Organization (WMO). Headquartered in Geneva, WMO is an intergovernmental organization that evolved in 1950 from its predecessor, the International Meteorological Organization. WMO is *the* specialized agency of the United Nations (UN) facilitating worldwide cooperation in meteorology, operational hydrology, and related geophysical sciences: 187 Member States and Territories participate (WMO 2004).

To fulfil this role, WMO undertakes a range of activities including the following:

(1) Facilitating the establishment of observational networks.
(2) Promoting the establishment and maintenance of (i) systems for the rapid exchange of meteorological and related information (primarily via the Global Telecommunication System [GTS]), and (ii) centres for the provision of meteorological and related services.
(3) Furthering the application of meteorology and operational hydrology to a range of human activities while encouraging close cooperation between meteorological and hydrological services.
(4) Encouraging research and training in meteorology and related fields.

The structure of WMO is based on an overarching body, The World Meteorological Congress, which is a quadrennial meeting of delegates of WMO Members to determine key policy, financial aspects, and regulatory aspects of WMO. The executive body of WMO is its Executive Council, comprising the directors of national meteorological or hydrometeorological services who meet annually to review the activities of WMO and to implement the programmes approved by the WMO Congress. There are eight technical commissions and ten major scientific and technical programmes, one of which is the cross-cutting Regional Programme (RP), which addresses relevant geophysical issues that are unique to, and of common concern within, a region.

Consistent with the spirit of cooperation that underpins globally based geophysical sciences, WMO has many interagency linkages; for example, oceanography and marine meteorology issues are dealt with through a joint technical commission in conjunction with the Intergovernmental Oceanographic Commission of the UN Educational Scientific and Cultural Organization.

In recognition that global issues may be better handled in subglobal units, there are six WMO Regional Associations (RAs): Africa, Asia, South America, North and Central America, South-West Pacific, and Europe. Each RA is composed of relevant WMO members, who coordinate meteorological and related activities within their respective regions.

The WMO Executive Council Working Group on Antarctic Meteorology (EC-WGAM) was established in 1964 to assume RA-type functions for the Antarctic (south of 60° S). The group's main task is to coordinate WMO's Antarctic Activities Programme (an RP) and in particular implement the World Weather Watch (WWW) basic components (especially observation and telecommunication networks) in the Antarctic. It also collaborates with other international organizations and programmes in operational and research activities in Antarctica, with, for example, the Scientific Committee on Antarctic Research and the Antarctic Treaty Consultative Meeting process.

EC-WGAM developed the Antarctic Basic Synoptic Network (ABSN), which is now an important element of the WWW Global Observing System: the operation and maintenance of the ABSN and the timely transmission of the observational data over the GTS are essential in the provision of meteorological data for global weather analysis and prediction and for climate research (WMO 2003).

STEVE PENDLEBURY

See also **Antarctic Treaty System; Meteorological Observing; Scientific Committee on Antarctic Research (SCAR); Weather Forecasting**

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WORSLEY, FRANK

If criteria for fame as an Antarctican included achievement on the continent itself, Frank Arthur Worsley would scarcely rate a mention, yet the captain of Sir Ernest Shackleton's ship *Endurance* left a powerful imprint.

Born in the New Zealand coastal settlement of Akaroa on February 22, 1872, Worsley went to sea as a teenager in the merchant navy, rounding Cape Horn on his first voyage. He served in both sail and steam, but sail was his passion, and he became a master navigator, learning about wind and wave, and of wildlife under and over the surface. He was eventually commissioned in the Royal Naval Reserve.

In 1914 Worsley joined Sir Ernest Shackleton's Imperial Trans-Antarctic Expedition (1914–1917) as the master of *Endurance,* the ship that was to deposit Shackleton and his party at the base of the Weddell Sea for a planned crossing of the Antarctic continent. Worsley and Shackleton shared many qualities and became good friends, brought together in peculiar circumstances. Shackleton selected him on hearing of "Worsley's Dream," in which Worsley saw himself navigating a ship through ice blocks down Burlington Street, London. He went there next day, found the expedition's headquarters, and met Shackleton, whose offer for being captain of the ship had recently been turned down by John King Davis.

After *Endurance* was crushed and the party drifted for months on the pack ice of the Weddell Sea, Worsley had his finest moments when three small boats were launched in April 1916. In charge of *Dudley Docker,* his navigation proved crucial in guiding the boats to the rocky dot of Elephant Island in a 5-day voyage that renewed hope for the men, some of whom were close to madness or death. That voyage was, in some senses, a more cruel and chilling experience than even the famed journey in the best of those small boats, *James Caird* (which had been built to Worsley's specifications).

Worsley was Shackleton's first choice for the six-man crew of *James Caird,* for his dead-reckoning skills and uncanny ability to snap sun-sightings and calculate positions in difficult conditions, as well as his proven small-boat sailing expertise. In the event, he navigated the small vessel about 800 miles (1300 km) from Elephant Island to South Georgia. The extraordinary 16-day journey—riding massive waves that hurtled endlessly around the boat—was possible only due to his seamanship, his navigating excellence, and the four sightings of the sun he managed under terrible conditions. At the end of the voyage, he brought *James Caird* back from disaster in a leeward storm to a safe landing.

After their arrival on the far side of South Georgia, from where help could be obtained at a whaling station, Worsley joined Shackleton and Tom Crean in crossing the virgin heights of the island, sealing their success. One sees in Worsley an extraordinary seaman with an explorer's heart.

Worsley commanded Q ships during World War I and was twice decorated for antisubmarine actions and while serving in the Russian theatre. He and Shackleton sailed together again on the Shackleton-Rowett Expedition of 1921–1922 on *Quest*. The two friends—notoriously bad money managers—dreamed of finding treasure, and they were hoping for a Pacific pearl lagoon as a finale to the expedition, a warmly anticipated period of pleasure sadly to end with Shackleton's untimely death at South Georgia.

In 1925 Worsley became joint leader of an expedition to Franz Josef Land, and a decade later he finally had his treasure hunt on Cocos Island, finding nothing. He retired from active work on the sea in 1939, becoming an instructor at the Royal Naval College, Greenwich. He died in England on February 1, 1943 from lung cancer, at the age of 70.

John Thomson

See also **Imperial Trans-Antarctic Expedition (1914–1917); Shackleton, Ernest; Shackleton–Rowett Antarctic Expedition (1921–1922)**

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Y

YELLOW-NOSED ALBATROSS

Following a DNA study of all the world's albatrosses (order Procellariiformes) in the 1990s, the species previously known as the yellow-nosed albatross *Diomedea chlororhynchos* was placed, along with rest of the "mollymawks" (the smaller Southern Ocean albatrosses), in the genus *Thalassarche* and split into two species. As itsname suggests, the Atlantic yellow-nosed albatross *T. chlororhynchos* is found over the South Atlantic Ocean, and its close congener, the Indian yellow-nosed albatross *T. carteri,* occurs over the southern Indian Ocean.

Both yellow-nosed albatrosses are small and predominantly black and white, with the upper ridge of the black bill yellow with an orange tip in adulthood. The two species may be distinguished in the hand by the shape of the upper end of this yellow stripe: rounded in Atlantic birds and pointed in Indian birds. Additionally, and allowing for identification at sea when in adult plumage, Atlantic birds have a pale grey head, whereas Indian birds have a white head. Juveniles, with all-black bills and white heads, are difficult to identify to species at sea.

Individuals of the Atlantic yellow-nosed albatross breed only at the Tristan da Cunha group of islands (United Kingdom): Tristan, Inaccessible, Nightingale, and Gough Islands. A breeding population of c. 36,800 breeding pairs suggests a global population of 165,000–185,000 birds. However, recent accurate surveys of breeding numbers are unavailable for all islands. Evidence from Gough Island shows a decreasing population of c. 5300 pairs. Individuals of the Indian species breed on the Prince Edward Islands (South Africa) and the three French island groups of Île Amsterdam and Île St. Paul, Îles Crozet, and Îles Kerguelen. Its total population has been estimated as 36,500 breeding pairs, which is known to be decreasing at some studied breeding sites.

Birds of both species occur at sea in the southern Atlantic and Indian Oceans between South America and New Zealand, but not in the Pacific Ocean. It is likely that individuals of both species are largely restricted to their own oceans.

Birds of both yellow-nosed albatross species are annual breeders, nesting more or less colonially on pedestal nest mounds made of scraped-up mud, in which a single egg is laid. In the Tristan group, birds nest among thick vegetation (ferns and *Phylica* trees), whereas Indian Ocean birds may breed on exposed cliffs and slopes at their more southerly sites. Breeding commences after 5 years or more, with both parents sharing incubation and chick-rearing. Fidelity to mate and nest site are high, as in all mollymawks, but divorce does sometimes occur. The pedestal nest may be reused for many seasons. Breeding success is typically of the order of 60%–70% but in some years can approach zero, as when a disease outbreak, perhaps human-introduced, kills chicks.

Individuals of both species feed on squid and fish, less commonly crustaceans, taken by surface-seizing and shallow plunges. Scavenging from fishing vessels occurs, leading to mortality as birds drown on baited longline hooks. Because of this, and their decreasing populations, both species have been classified as Endangered (very high risk of extinction) by BirdLife International on behalf of the World Conservation Union.

JOHN COOPER

See also **Albatrosses: Overview; Amsterdam Island (Île Amsterdam); Crozet Islands (Îles Crozet); Diseases, Wildlife; Fish: Overview; Gough Island; Kerguelen Islands (Îles Kerguelen); Squid; St. Paul Island (Île St. Paul)**

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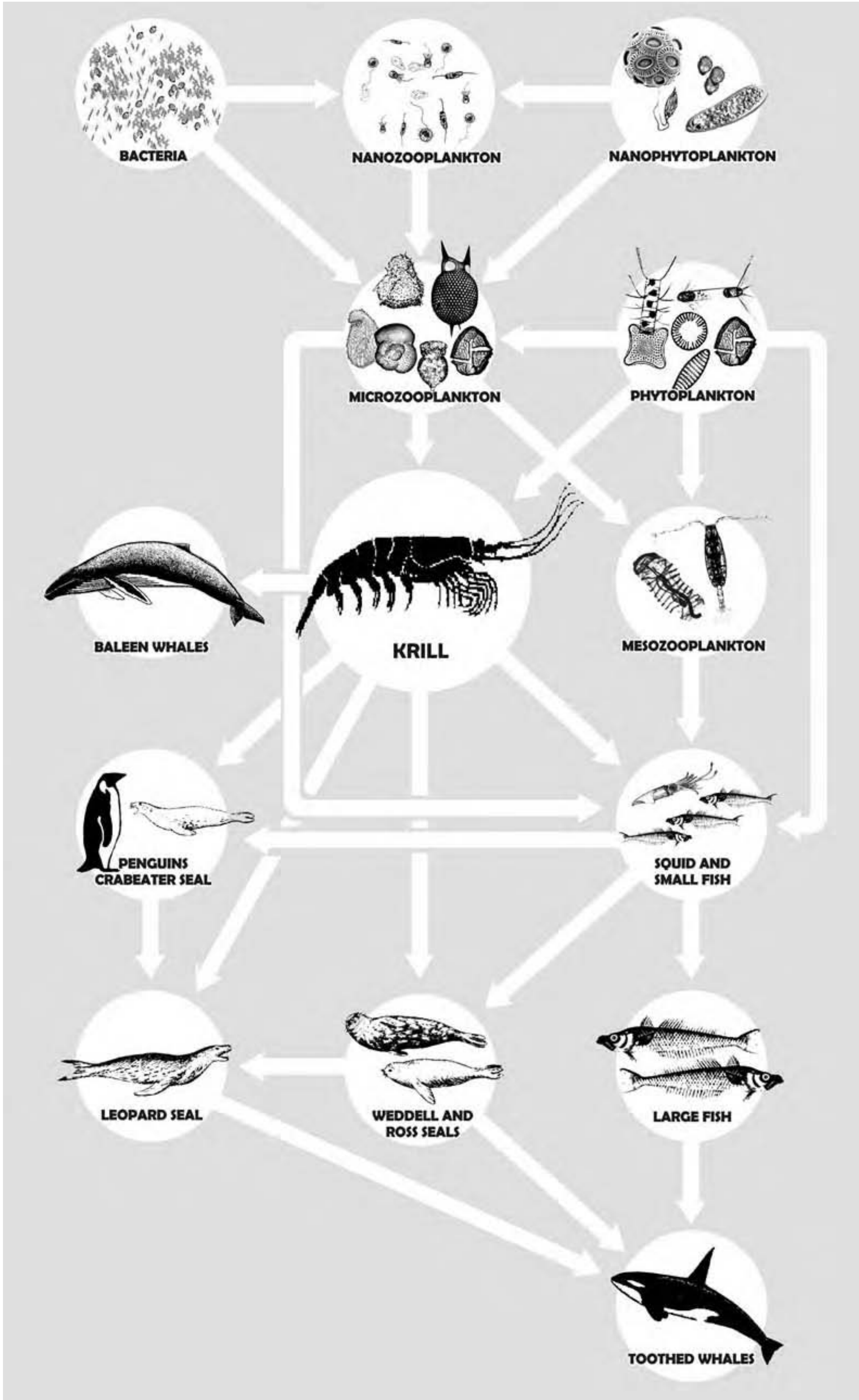
Z

ZOOPLANKTON AND KRILL

Zooplankton are marine or freshwater animals that live in suspension in the water column, from the surface to abyssal oceanic depths (>10,000 m). The swimming capabilities of these organisms are not strong enough to preclude their horizontal distribution from being governed by currents, but most are capable of maintaining a preferred depth range, and many can migrate vertically tens to hundreds of meters daily. Zooplankton include a diverse range of organisms: many single-celled organisms, often with elaborate calcareous or siliceous skeletons (Foraminifera, Radiolaria); gelatinous predatory (Hydromedusae, Siphonophorae, Scyphozoa, Ctenophora, Polychaeta, Chaetognatha) and particle-filtering forms (Pteropoda, Appendicularia, Salpidae); many crustaceans (Cladocera, Ostracoda, Copepoda); fish larvae; etc. The term "plankton," which encompasses plants (phytoplankton) and animals (zooplankton), is derived from the Greek "planktos," meaning wandering or drifting. Its first use is ascribed to the German biologist Viktor Hensen in 1887.

Zooplankton can be classified according to size, life-cycle traits, morphology, feeding mode, etc. Classifications based on size, most useful for methodological purposes (most plankton sampling gears are size-selective), recognize seven size categories, ranging from ultrananoplankton (below 2 µm; bacteria, viruses) to megaloplankton (>20 cm; many jellyfish). Holoplankters are those organisms that spend their entire life cycle in the water column, as opposed to meroplankters, which are nonplanktonic at some stage in their lives. For example, most marine benthic (bottom-dwelling) animals, like starfish, clams, mussels, snails, worms, and crabs, have a planktonic stage represented by their gametes (sperm and ova) and larvae. Also, the early stages of fish and squid are part of the plankton until they grow large enough to become strong swimmers, at which time they are considered to belong to the nekton.

In total, c. 7000 species of marine zooplanktonic animals have been described, distributed among approximately 30 groups. The most speciose holoplankters are the copepods, a group of small (around 1 mm) crustaceans for which over 2000 free-living marine planktonic species are known. A few groups have 300–600 species (e.g., other crustaceans like Mysidacea and Amphipoda, the Hydromedusae [a group of small jellyfish], and the single-celled Radiolaria and Tintinnina), with most others ranging around 50–100 described species worldwide. Although most zooplanktonic taxa have representatives south of the Polar Front, the numbers of Antarctic species are very variable between groups: some are almost absent from the area (like the single-celled Acantharia, or the Heteropoda [planktonic snails]), while others are very well represented. The most conspicuous zooplanktonic organisms are the crustaceans (Copepoda, with over 100 species; Euphausiacea; Amphipoda; Ostracoda), followed by Chaetognatha, Salpidae, Polychaeta, Phaeodaria, and Appendicularia. However, on average, the waters around Antarctica are relatively



Simplified scheme of Antarctic food web.

species poor, hosting some 1500 described holoplanktonic species (as compared with 5000–6000 for the Tropics and sub-Tropics).

Probably the most important Antarctic zooplankter is *Euphausia superba* or krill—a shrimp-like crustacean of the order Euphausiacea (the term "krill" is also applied to any of the c. eighty species of these planktonic crustaceans). Krill have an elongated head–trunk region (cephalothorax) where the food gathering, manipulating, and grinding limbs are inserted, and a muscular, segmented tail (abdomen) provided with five pairs of paddle-like swimming legs. Adult individuals are approximately 6 cm in length and weigh over a gram. Their body is reddish-transparent, with large black eyes and bioluminescent organs (photophores) on the lower side, but dead and preserved specimens are opaque. Krill feed mainly on phytoplankton, but planktonic animals are common in their diet as well.

The abundance of zooplankters in sea water is roughly inversely proportional to their size. Thus, bacteria, at less than 1 μm in diameter, are present in densities around 10^8–10^9 l^{-1}; protist concentrations (ciliates, Foraminifera, Radiolaria), whose size ranges from 10–100 μm, are usually around 10 to 10^3 l^{-1}; medusae (Hydromedusae), whose bodies measure around 5–15 mm, seldom reach densities over 0.05 l^{-1}; etc. But as opposed to diversity, abundance of zooplankton is not associated with latitude. The richest areas in numbers of individuals are located along the continental shelves. Antarctic waters have generally moderate to low zooplanktonic abundances, except during the short austral summer, when reproductive activity is concentrated. One notable exception is krill, which form huge swarms up to several hundreds of meters across, with densities of over 20 animals per liter and up to 15–20 kg per m^3. Stocks of krill around Antarctica are estimated at 300 to 1000 million metric tonnes, with a potentially sustainable harvest of 150 million metric tonnes a year (more than that of all other oceanic species of fish and shellfish throughout the world combined).

One of the most outstanding features of the Southern Ocean is its extreme seasonal cyclicity, whereby the scarcity of light in the ice-covered waters determines a strongly food-limited winter, which alternates with an ice-free season when phytoplankton growth is active in the water column. The life cycle of most Antarctic zooplankters is finely tuned to these changes.

Most herbivorous copepods (e.g., *Calanus propinquus, Calanoides acutus,* and many others) feed actively on the early-spring (October) phytoplankton bloom and shortly thereafter reproduce in the surface waters. Newborns graze vigorously in these upper phytoplankton-rich layers throughout the summer, and as they grow they sink in the water column. By May, when the pack ice starts waxing and food becomes scarce, they have reached an advanced larval stage and are located in deeper waters (250 to over 1000 m, depending on the species). Here they spend the winter in a dormant state, rising back to the surface in spring, where they feed, mature, and reproduce.

Other organisms, while also finely tuned to Antarctic seasonality, have a different reproductive strategy. *Euphausia superba* (krill) spawns in the upper layers (each female may lay up to 10,000 eggs at a time) and the fertilized eggs slowly sink; at 2000–3000 m the newborn hatch and start swimming upwards. They reach the surface in an early larval stage and start grazing. During their first year krill complete their nine-stage larval development, during the second year they graze and accumulate reserves, and by the third year of life they mature sexually and reproduce. During the summer, *E. superba* is an active filterer of the microplankton suspended in the water column, but during the winter, when food particles in the water are very scarce, it scrapes the undersurface of the ice pack, harvesting algae and other microorganisms.

Zooplanktonic organisms are key elements in marine food webs. They are active consumers of phytoplankton, and are in turn fed upon by other zooplankton, cephalopods, fish, and marine birds and mammals. In some areas, like the Southern Ocean, their importance is enhanced by the fact that the single-celled sarcodines and ciliates feed upon the abundant nanoplanktonic and ultrananoplanktonic particles (bacteria, autotrophic flagellates), and are in turn consumed by larger zooplankters, like copepods and euphausiids. The size of these bacteria and flagellates is too small for the larger zooplankters to efficiently feed on them; thus, the protists convert the organic matter into a size more easily available to higher levels of the food web. On the other hand, the grazing and predatory activity of some zooplankters can be so intense that they strongly affect the abundance and biomass of other plankton, including fish larvae, thus reducing fish populations. In the Southern Ocean, krill is a key component of food webs as it constitutes the major direct or indirect source of food of most of the larger Antarctic animals, such as fish, squid, seabirds, seals, and whales.

The abundance of krill has called the attention of scientists and fishers since its discovery, and in the early 1970s commercial fishing was started in Southern Ocean waters. Krill landings increased swiftly from 59 tonnes in 1973 to c. 50,000 tonnes in 1982–1986 (with a drop to c. 200,000 tonnes in 1983–1985, probably partly due to the Argentina–United

Kingdom war over the Falkland Islands). However, between 1987 and 1993, catches shrank to around 100,000 tonnes, remaining at those levels until the present (in the 2002–2003 season 116,866 tonnes of krill were caught by a total of five countries: Japan, South Korea, Ukraine, the United States, and Poland, with the first three accounting for over 80% of the catch). The main reason for this decline is the remoteness of the area. Profitability is also reduced by the fact that krill has powerful enzymes that break down its tissues soon after death, spoiling the catch, and the high concentrations of fluoride in the shell (which is toxic and has to be removed before the meat is fit for consumption). In addition, market demand for krill has decreased in the last decade in association with the strong worldwide increase in the production of farmed shrimp. In 1991, the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) set a precautionary catch limit of about 10% of the biomass, but since 1993, catches have been far below these threshold values. Krill biomass, however, has also decreased considerably over the past century. In the southwest Atlantic sector, which contains >50% of Southern Ocean krill stocks, mean densities have declined significantly since the 1970s, probably as a response to waning winter ice coverage.

While krill has a circumpolar distribution, the highest concentrations are found in the area around South Georgia and the Antarctic Peninsula, which is where most of the fishing activities take place. Krill are caught by large freezer trawlers and processed on board into products for consumption by humans, domestic animals (cattle, poultry, pigs), and farmed fish, and for sport fishing bait. Krill are especially rich in vitamin A.

Demetrio Boltovskoy and Andrés Boltovskoy

See also **Antarctic Fur Seal; Cetaceans, Small: Overview; Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR); Food Web, Marine; Phytoplankton; Seasonality; South Georgia**

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Appendix I: Chronology of Antarctic Exploration

Years	Expedition	Leader	Vessel
1487–88	**Portuguese Naval Expedition** Discovered and rounded Cape of Good Hope and reached southern limit of Africa at Cape Agulhas, opening a sea route to Indian Ocean	**Bartholomeu Diaz de Novaes**	
1497–99	**Portuguese Naval Expedition** Discovered sea passage around southern tip of Africa to India	**Vasco da Gama**	***São Gabriel* & 3 other ships**
1501–02	**Portuguese Maritime Voyage** Reported land at 52° S, possibly Patagonia	**Amerigo Vespucci (pilot)**	
1506	**Portuguese Naval Voyage** Discovered Tristan de Cunha group	**Tristão da Cunha**	***Santiago* & 13 other ships**
1519–22	**Spanish Maritime Voyage** Discovered Strait of Magellan and Tierra del Fuego; completed first circumnavigation	**Ferdinand Magellan**	***Vittoria* & 4 other ships**
1577–80	**English Maritime Voyage** Discovered Drake Passage and proved Tierra del Fuego was not part of "Terra Australis Incognita"; completed second circumnavigation	**Francis Drake**	***Pelican (Golden Hind)* & 4 other ships**
1592	**English Naval Expedition** Discovered Falkland Islands	**John Davis**	**HMS *Desire***
1615–16	**Netherlands Exploring Expedition** Discovered Cape Horn and Le Maire Strait	**Jakob Le Maire**	***Eendracht* & *Hoorn***
1617–18	**Netherlands Voyage** Discovered Île St. Paul	**Haevik Klaaszoon van Hillegom**	***Zeewolf***
1663	**Netherlands Voyage** Discovered what might have been Prince Edward Islands	**Barend Barendszoon Lam**	***Maerseveen***
1674–75	**English Mercantile Voyage** Discovered what was probably South Georgia	**Antonio de la Roche**	
1738–39	**French Exploring Voyage** Discovered Bouvetøya	**Jean-Baptiste Bouvet de Lozier**	***Aigle* & *Marie***
1768–71	**British Naval Expedition** Explored Tierra del Fuego and Drake Passage; made discoveries in Australia and New Zealand	**James Cook**	***Endeavour***
1771–72	**French Exploring Expedition** Discovered Îles Kerguelen	**Yves-Joseph de Kerguelen-Trémarec**	***Fortune* & *Gros-Ventre***
1771–73	**French Exploring Expedition** Discovered Îles Crozet	**Marc Macé Marion du Fresne**	***Mascarin***
1772–75	**British Naval Expedition** First crossing of Antarctic Circle; attained farthest south of 71°10′ S; claimed South Georgia; discovered South Sandwich Islands; completed circumnavigation in a high southern latitude	**James Cook**	***Resolution* & *Adventure***
1773–74	**French Naval Expedition** Revisited and charted Îles Kerguelen	**Yves-Joseph de Kerguelen-Trémarec**	***Rolland* & 2 other ships**
1776–80	**British Naval Expedition** Visited and named Prince Edward Islands; visited Îles Crozet and Îles Kerguelen	**James Cook**	***Resolution* & *Discovery***

Years	Expedition	Leader	Vessel
1805–06	**British Whaling Voyage** Discovered Auckland Islands	**Abraham Bristow**	***Ocean***
1809–10	**New South Wales Sealing Voyage** Discovered Campbell Island	**Frederick Hasselburg**	***Perseverance***
1810	**New South Wales Sealing Voyage** Discovered Macquarie Island	**Frederick Hasselburg**	***Perseverance***
1819	**British Mercantile Voyage** Discovered South Shetland Islands	**William Smith**	***Williams***
1819–20	**British Exploring Expedition** Surveyed South Shetland Islands; discovered Trinity Land; took possession of King George Island and Clarence Island	**Edward Bransfield (senior naval officer)**	***Williams***
1819–21	**Russian Naval Expedition** Circumnavigated Antarctic continent; made first confirmed sighting of Antarctic continent; discovered Peter I Øy and Alexander Island	**Fabian von Bellingshausen**	***Vostok* & *Mirnyy***
1820–21	**US Sealing Voyage** Nathaniel Palmer in *Hero* reported land that was later named Palmer Land	**Benjamin Pendleton**	***Frederick* & 5 other ships**
1820–22	**US Sealing Voyage** Made first confirmed landing on the mainland coast of Antarctica	**John Davis**	***Huron* & 2 other ships**
1821–22	**British Sealing Voyage** In company with Nathaniel Palmer *(James Monroe)*, discovered and charted South Orkney Islands	**George Powell**	***Dove* & *Eliza***
1821–22	**US Sealing Voyage** In company with George Powell, Nathaniel Palmer *(James Monroe)* discovered and charted South Orkney Islands	**Benjamin Pendleton**	***Frederick* & 6 other ships**
1822–24	**British Sealing Voyage** Established farthest south of 74°15′ S in Weddell Sea	**James Weddell**	***Jane***
1828–31	**British Naval Expedition** Visited South Shetland Islands to make pendulum and magnetic observations on Deception Island	**Henry Foster**	**HMS *Chanticleer***
1829–31	**US Sealing Voyage** First US government-sponsored Antarctic expedition	**Benjamin Pendleton**	***Seraph* & 2 other ships**
1830–33	**British Exploring Expedition** Discovered Enderby Land and Graham Land	**John Biscoe**	***Tula* & *Lively***
1833–34	**British Expedition** Discovered Heard Island and Kemp Land	**Peter Kemp**	***Magnet***
1837–40	**French Naval Expedition** Circumnavigation; explored much of Antarctic coast; discovered Terre Adélie; first saw Adélie penguins	**Jules-Sébastien-César Dumont d'Urville**	***Astrolabe* & *Zélée***
1838–42	**US South Seas Exploring Expedition** Discovered Wilkes Land and some 1500 miles of "coastline"; published expedition charts were first to use term "Antarctic Continent"	**Charles Wilkes**	***Vincennes* & 5 other ships**
1839–43	**British Naval Expedition** Circumnavigated continent; first to pass through pack ice to reach Ross Sea; discovered Victoria Land and charted 550 miles of it; discovered Ross Island, Ross Ice Shelf	**James Clark Ross**	**HMS *Erebus* & HMS *Terror***

1853–54	**British Voyage**	**William McDonald**	***Samarang***
	Discovered McDonald Islands		
1872–76	**British Naval & Scientific Voyage**	**George Strong Nares (1872–74)** **Frank Tourle Thompson (1875–76)**	**HMS *Challenger***
	Conducted oceanographic research while making circumnavigation; first steamship to cross the Antarctic Circle; visited many sub-Antarctic islands		
1873–74	**German Sealing & Exploring Expedition**	**Eduard Dallmann**	***Grönland***
	Visited South Shetland Islands and South Orkney Islands; charted coast and islands in region of Bismarck Strait		
1882–83	**German International Polar Year Expedition**	**Karl Schrader (Leader)**	
	Established scientific station and conducted scientific studies for more than a year		
1892–93	**Dundee Whaling Expedition**		**4 ships**
	Reconnaissance to investigate Antarctic whaling possibilities; W.S. Bruce and others conducted scientific programs		
1892–93	**Norwegian (Sandefjord) Whaling Expedition**	**Carl Larsen**	***Jason***
	Reconnaissance to investigate Antarctic whaling possibilities in Antarctic Peninsula region		
1893–94	**Norwegian (Sandefjord) Expedition**	**Carl Larsen**	***Jason* & 2 other ships**
	Exploratory and whaling and sealing expedition; discovered King Oscar II Coast, Foyn Coast, and Robertson Island; first use of ski in Antarctica		
1893–95	**Norwegian (Tønsberg) Whaling Expedition**	**Henrik Bull**	***Antarctic***
	Reconnaissance to investigate Antarctic whaling possibilities; landing at Cape Adare widely considered at the time to be the first landing on the continent		
1897–99	**Belgian Antarctic Expedition**	**Adrien de Gerlache**	***Belgica***
	International party discovered and mapped parts of the Antarctic Peninsula and nearby islands; first wintering south of the Antarctic Circle		
1898–1900	**British Antarctic Expedition**	**Carsten Borchgrevink**	***Southern Cross***
	First party to winter on Antarctic continent (Cape Adare); made pioneer scientific investigations; travelled south on Ross Ice Shelf		
1901–03	**German South Polar Expedition**	**Erich von Drygalski**	***Gauss***
	Wintered in ice pack; discovered Wilhelm II Land and Gaussberg		
1901–04	**Swedish South Polar Expedition**	**Otto Nordenskjöld**	***Antarctic***
	Conducted comprehensive scientific program; parties wintered at Snow Hill Island, Hope Bay, and Paulet Island; ship sank		
1901–04	**British National Antarctic Expedition**	**Robert Falcon Scott**	***Discovery***
	Conducted comprehensive scientific program; wintered at Hut Point on Ross Island; discovered King Edward VII Land; attained farthest south of 82°17′ S on Ross Ice Shelf		
1902–04	**Scottish National Antarctic Expedition**	**William Speirs Bruce**	***Scotia***
	Conducted comprehensive scientific program; first oceanographic investigation of Weddell Sea; established meteorological observatory on Laurie Island		
1903	**Argentine Relief Expedition**	**Julian Irîzar**	***Uruguay***
	Rescued members of the Swedish South Polar Expedition		
1903–04	**British Relief Expedition**	**William Colbeck** **Henry Duncan Mackay**	***Morning*** ***Terra Nova***
	Relieved *Discovery* and expedited return of British National Antarctic Expedition		
1903–05	**French Antarctic Expedition**	**Jean-Baptiste Charcot**	***Français***
	Explored and charted islands to west of Antarctic Peninsula; conducted comprehensive scientific program		

Years	Expedition	Leader	Vessel
1904–05	**Establishment of Whaling Base**	**Carl Larsen**	
	Compañia Argentina de Pesca established first Antarctic whaling station at Grytviken, South Georgia		
1907–09	**British Antarctic Expedition**	**Ernest Shackleton**	***Nimrod***
	Wintered at Cape Royds on Ross Island; made first ascent of Mount Erebus; discovered Beardmore Glacier; attained farthest south of 88°23′ S on Polar Plateau; reached region of the South Magnetic Pole		
1908–10	**French Antarctic Expedition**	**Jean-Baptiste Charcot**	***Pourquoi Pas?***
	Explored and charted west coast of Antarctic Peninsula and local islands; conducted comprehensive scientific program		
1910–12	**Norwegian South Polar Expedition**	**Roald Amundsen**	***Fram***
	Wintered on Ross Ice Shelf near Bay of Whales; party of five first to attain South Pole; explored King Edward VII Land		
1910–12	**Japanese Antarctic Expedition**	**Nobu Shirase**	***Kainan-Maru***
	Explored King Edward VII Land		
1910–13	**British South Polar Expedition**	**Robert Falcon Scott**	***Terra Nova***
	Wintered at multiple sites; conducted comprehensive scientific program; party of five second to attain South Pole, but all died on return		
1911–12	**German South Polar Expedition**	**Wilhelm Filchner**	***Deutschland***
	Discovered Filchner Ice Shelf; ship beset and drifted in pack for nine months		
1911–14	**Australasian Antarctic Expedition**	**Douglas Mawson**	***Aurora***
	Wintered at Macquarie Island, Cape Denison, and Shackleton Ice Shelf; conducted most comprehensive scientific program yet at the time, including oceanographic cruises; discovered and explored King George V Land and Queen Mary Land		
1914–16	**Imperial Trans-Antarctic Expedition, Weddell Sea Party**	**Ernest Shackleton**	***Endurance***
	Ship beset and drifted 10 months in Weddell Sea; ship crushed and sank; company reached Elephant Island; six men sailed to South Georgia to organise relief		
1914–17	**Imperial Trans-Antarctic Expedition, Ross Sea Party**	**Æneas Mackintosh**	***Aurora***
	Laid depots for Shackleton's proposed crossing of Antarctica; ship beset and drifted 10 months; land party relieved after three men had died		
1920–22	**British Imperial Expedition**	**John Cope**	
	Two men wintered at Waterboat Point, Antarctic Peninsula; conducted scientific program		
1921–22	**Shackleton-Rowett Antarctic Expedition**	**Ernest Shackleton; Frank Wild**	***Quest***
	Visited South Georgia (where Shackleton died), Weddell Sea, and a series of sub-Antarctic islands		
1923–24	**Norwegian Whaling Expedition**	**Carl Larsen**	***James Clark Ross***
	Initial whaling expedition to the Ross Sea		
1925–51	**Discovery Investigations**	**Neil Alison Mackintosh and others**	***Discovery, William Scoresby, & Discovery II***
	Series of expeditions engaging in long-term series of scientific programs		
1927–37	**Christensen Antarctic Expeditions**		
	Series of seven expeditions promoted by Lars Christensen; explored and claimed Norwegian sector of mainland; landed on and claimed Bouvetøya and Peter I Øy for Norway; made flights over coastal and inland areas; engaged in whaling		
1928–29	**Wilkins-Hearst Antarctic Expedition**	**Hubert Wilkins**	***Hektoria***
	First powered flight in Antarctica		

1928–30	**US Antarctic Expedition**	**Richard E. Byrd**	***City of New York* & 2 other ships**
	Wintered at "Little America" at Bay of Whales; explored various regions; first flight over the South Pole		
1929–30	**British Aerial Expedition**	**Hubert Wilkins**	
	Extended Wilkins' previous aerial reconnaissance of Antarctic Peninsula region		
1929–31	**British, Australian, New Zealand Antarctic Research Expedition**	**Douglas Mawson**	***Discovery***
	Discovered and charted various coasts, helping establish claim for Australian Antarctic Territory		
1933–34	**US Aerial Expedition**	**Lincoln Ellsworth**	***Wyatt Earp***
	Plan to fly across Antarctic continent from Ross Sea to Antarctic Peninsula postponed due to plane crash		
1933–35	**US Byrd Antarctic Expedition**	**Richard E. Byrd**	***Bear of Oakland* & *Jacob Ruppert***
	Wintered at "Little America II" at Bay of Whales; engaged in broad scientific and geographical research program		
1934–35	**US Aerial Expedition**	**Lincoln Ellsworth**	***Wyatt Earp***
	Plan to fly across Antarctic continent from Antarctic Peninsula to Ross Sea postponed due to bad weather; flight made along east coast of Peninsula		
1934–37	**British Graham Land Expedition**	**John Rymill**	***Penola***
	Conducted extensive scientific program; engaged in sledging and aerial geographical surveys		
1935–36	**Ellsworth Trans-Antarctic Flight**	**Lincoln Ellsworth**	***Wyatt Earp***
	Ellsworth & Herbert Hollick-Kenyon made first flight across Antarctic continent		
1938–39	**German Antarctic Expedition**	**Alfred Ritscher**	***Schwabenland***
	Conducted aerial reconnaissance and photography in Dronning Maud Land; claimed areas for Germany		
1939–41	**US Antarctic Service Expedition**	**Richard E. Byrd**	**USNS *North Star* & USS *Bear***
	Wintered at "Little America III" at Bay of Whales and at Stonington Island; conducted comprehensive scientific program and aerial reconnaissance		
1943–44	**British Naval "Operation Tabarin"**	**J. W. S. Marr**	
	Established permanent stations at Port Lockroy and Deception Island; carried out broad scientific program		
1944–45	**British Naval "Operation Tabarin II"**	**Andrew Taylor**	
	Established station at Hope Bay; built hut at Sandefjord Bay, Coronation Island; carried out broad scientific program		
1945–46	**Falkland Islands Dependencies Survey Expedition**	**Edward Bingham**	**3 ships**
	Officially took over responsibility for British stations from Operation Tabarin; established two new bases; conducted scientific and survey program		
1946–47	**US Navy Antarctic Developments Project ("Operation Highjump")**	**Richard E. Byrd**	**13 ships**
	Naval taskforce divided into three main groups with emphasis on naval training and aerial photographic reconnaissance; second flight over the South Pole; limited scientific program		
1947–48	**Australian National Antarctic Research Expedition**	**Stuart Campbell**	**HST *3501***
	Established research station on Heard Island and Macquarie Island and long-term scientific programs begun at both stations		
1947–48	**US Navy Antarctic Developments Project ("Operation Windmill")**	**Gerald L. Ketchum**	**USS *Burton Island* & USS *Edisto***
	Primary task to secure ground control for aerial photographs taken during Operation Highjump		

Years	Expedition	Leader	Vessel
1947–48	**Ronne Antarctic Research Expedition**	**Finn Ronne**	***Port of Beaumont***
	Wintered at Stonington Island; limited scientific and geographical programs; first two women to winter on Antarctic continent: Jennie Darlington and Edith "Jackie" Ronne		
1949–52	**Norwegian–British–Swedish Antarctic Expedition**	**John Giæver**	***Norsel***
	Established base of Maudheim; conducted comprehensive scientific program and extensive aerial survey		
1955–57	**Falkland Islands Dependencies Aerial Survey Expedition**	**Peter Mott**	***Oluf Sven***
	Program of vertical aerial photography of Falkland Islands, South Shetland Islands, and Antarctic Peninsula		
1955–58	**Commonwealth Trans-Antarctic Expedition**	**Vivian Fuchs**	**3 ships**
	First surface crossing of the Antarctic continent from "Shackleton base" on Filchner Ice Shelf to Scott Base on Ross Island via South Pole; comprehensive scientific program and aerial and surface reconnaissance and survey conducted		
1957–58	**International Geophysical Year**		
	World-wide cooperative research program involving 66 nations, of which 12 had bases in Antarctica, including during years immediately preceding and following the IGY		

Appendix II: The Antarctic Treaty

The Governments of Argentina, Australia, Belgium, Chile, the French Republic, Japan, New Zealand, Norway, the Union of South Africa, the Union of Soviet Socialist Republics, the United Kingdom of Great Britain and Northern Ireland, and the United States of America,

Recognizing that it is in the interest of all mankind that Antarctica shall continue for ever to be used exclusively for peaceful purposes and shall not become the scene or object of international discord;

Acknowledging the substantial contributions to scientific knowledge resulting from international cooperation in scientific investigation in Antarctica;

Convinced that the establishment of a firm foundation for the continuation and development of such cooperation on the basis of freedom of scientific investigation in Antarctica as applied during the International Geophysical Year accords with the interests of science and the progress of all mankind;

Convinced also that a treaty ensuring the use of Antarctica for peaceful purposes only and the continuance of international harmony in Antarctica will further the purposes and principles embodied in the Charter of the United Nations;

Have agreed as follows:

Article I

1. Antarctica shall be used for peaceful purposes only. There shall be prohibited, *inter alia,* any measure of a military nature, such as the establishment of military bases and fortifications, the carrying out of military manoeuvres, as well as the testing of any type of weapon.
2. The present Treaty shall not prevent the use of military personnel or equipment for scientific research or for any other peaceful purpose.

Article II

Freedom of scientific investigation in Antarctica and cooperation toward that end, as applied during the International Geophysical Year, shall continue, subject to the provisions of the present Treaty.

Article III

1. In order to promote international cooperation in scientific investigation in Antarctica, as provided for in Article II of the present Treaty, the Contracting Parties agree that, to the greatest extent feasible and practicable:

   a. information regarding plans for scientific programs in Antarctica shall be exchanged to permit maximum economy of and efficiency of operations;
   b. scientific personnel shall be exchanged in Antarctica between expeditions and stations;
   c. scientific observations and results from Antarctica shall be exchanged and made freely available.

2. In implementing this Article, every encouragement shall be given to the establishment of cooperative working relations with those Specialized Agencies of the United Nations and other technical organizations having a scientific or technical interest in Antarctica.

Article IV

1. Nothing contained in the present Treaty shall be interpreted as:

   a. a renunciation by any Contracting Party of previously asserted rights of or claims to territorial sovereignty in Antarctica;
   b. a renunciation or diminution by any Contracting Party of any basis of claim to territorial sovereignty in Antarctica which it may have whether as a result of its activities or those of its nationals in Antarctica, or otherwise;
   c. prejudicing the position of any Contracting Party as regards its recognition or non-recognition of any other State's rights of

or claim or basis of claim to territorial sovereignty in Antarctica.

2. No acts or activities taking place while the present Treaty is in force shall constitute a basis for asserting, supporting or denying a claim to territorial sovereignty in Antarctica or create any rights of sovereignty in Antarctica. No new claim, or enlargement of an existing claim, to territorial sovereignty in Antarctica shall be asserted while the present Treaty is in force.

Article V

1. Any nuclear explosions in Antarctica and the disposal there of radioactive waste material shall be prohibited.
2. In the event of the conclusion of international agreements concerning the use of nuclear energy, including nuclear explosions and the disposal of radioactive waste material, to which all of the Contracting Parties whose representatives are entitled to participate in the meetings provided for under Article IX are parties, the rules established under such agreements shall apply in Antarctica.

Article VI

The provisions of the present Treaty shall apply to the area south of 60° South Latitude, including all ice shelves, but nothing in the present Treaty shall prejudice or in any way affect the rights, or the exercise of the rights, of any State under international law with regard to the high seas within that area.

Article VII

1. In order to promote the objectives and ensure the observance of the provisions of the present Treaty, each Contracting Party whose representatives are entitled to participate in the meetings referred to in Article IX of the Treaty shall have the right to designate observers to carry out any inspection provided for by the present Article. Observers shall be nationals of the Contracting Parties which designate them. The names of observers shall be communicated to every other Contracting Party having the right to designate observers, and like notice shall be given of the termination of their appointment.
2. Each observer designated in accordance with the provisions of paragraph 1 of this Article shall have complete freedom of access at any time to any or all areas of Antarctica.
3. All areas of Antarctica, including all stations, installations and equipment within those areas, and all ships and aircraft at points of discharging or embarking cargoes or personnel in Antarctica, shall be open at all times to inspection by any observers designated in accordance with paragraph 1 of this Article.
4. Aerial observation may be carried out at any time over any or all areas of Antarctica by any of the Contracting Parties having the right to designate observers.
5. Each Contracting Party shall, at the time when the present Treaty enters into force for it, inform the other Contracting Parties, and thereafter shall give them notice in advance, of

   a. all expeditions to and within Antarctica, on the part of its ships or nationals, and all expeditions to Antarctica organized in or proceeding from its territory;
   b. all stations in Antarctica occupied by its nationals; and
   c. any military personnel or equipment intended to be introduced by it into Antarctica subject to the conditions prescribed in paragraph 2 of Article I of the present Treaty.

Article VIII

1. In order to facilitate the exercise of their functions under the present Treaty, and without prejudice to the respective positions of the Contracting Parties relating to jurisdiction over all other persons in Antarctica, observers designated under paragraph 1 of Article VII and scientific personnel exchanged under sub-paragraph 1(b) of Article III of the Treaty, and members of the staffs accompanying any such persons, shall be subject only to the jurisdiction of the Contracting Party of which they are nationals in respect of all acts or omissions occurring while they are in Antarctica for the purpose of exercising their functions.

2. Without prejudice to the provisions of paragraph 1 of this Article, and pending the adoption of measures in pursuance of subparagraph 1(e) of Article IX, the Contracting Parties concerned in any case of dispute with regard to the exercise of jurisdiction in Antarctica shall immediately consult together with a view to reaching a mutually acceptable solution.

Article IX

1. Representatives of the Contracting Parties named in the preamble to the present Treaty shall meet at the City of Canberra within two months after the date of entry into force of the Treaty, and thereafter at suitable intervals and places, for the purpose of exchanging information, consulting together on matters of common interest pertaining to Antarctica, and formulating and considering, and recommending to their Governments, measures in furtherance of the principles and objectives of the Treaty, including measures regarding:

   a. use of Antarctica for peaceful purposes only;
   b. facilitation of scientific research in Antarctica;
   c. facilitation of international scientific cooperation in Antarctica;
   d. facilitation of the exercise of the rights of inspection provided for in Article VII of the Treaty;
   e. questions relating to the exercise of jurisdiction in Antarctica;
   f. preservation and conservation of living resources in Antarctica.

2. Each Contracting Party which has become a party to the present Treaty by accession under Article XIII shall be entitled to appoint representatives to participate in the meetings referred to in paragraph 1 of the present Article, during such times as that Contracting Party demonstrates its interest in Antarctica by conducting substantial research activity there, such as the establishment of a scientific station or the dispatch of a scientific expedition.
3. Reports from the observers referred to in Article VII of the present Treaty shall be transmitted to the representatives of the Contracting Parties participating in the meetings referred to in paragraph 1 of the present Article.
4. The measures referred to in paragraph 1 of this Article shall become effective when approved by all the Contracting Parties whose representatives were entitled to participate in the meetings held to consider those measures.
5. Any or all of the rights established in the present Treaty may be exercised as from the date of entry into force of the Treaty whether or not any measures facilitating the exercise of such rights have been proposed, considered or approved as provided in this Article.

Article X

Each of the Contracting Parties undertakes to exert appropriate efforts, consistent with the Charter of the United Nations, to the end that no one engages in any activity in Antarctica contrary to the principles or purposes of the present Treaty.

Article XI

1. If any dispute arises between two or more of the Contracting Parties concerning the interpretation or application of the present Treaty, those Contracting Parties shall consult among themselves with a view to having the dispute resolved by negotiation, inquiry, mediation, conciliation, arbitration, judicial settlement or other peaceful means of their own choice.
2. Any dispute of this character not so resolved shall, with the consent, in each case, of all parties to the dispute, be referred to the International Court of Justice for settlement; but failure to reach agreement on reference to the International Court shall not absolve parties to the dispute from the responsibility of continuing to seek to resolve it by any of the various peaceful means referred to in paragraph 1 of this Article.

Article XII

1. a. The present Treaty may be modified or amended at any time by unanimous agreement of the Contracting Parties whose representatives are entitled to participate in the meetings provided for under Article IX. Any such modification or amendment shall enter into force when the depositary Government has received notice from all such Contracting Parties that they have ratified it.

b. Such modification or amendment shall thereafter enter into force as to any other Contracting Party when notice of ratification by it has been received by the depositary Government. Any such Contracting Party from which no notice of ratification is received within a period of two years from the date of entry into force of the modification or amendment in accordance with the provision of subparagraph 1(a) of this Article shall be deemed to have withdrawn from the present Treaty on the date of the expiration of such period.

2. a. If after the expiration of thirty years from the date of entry into force of the present Treaty, any of the Contracting Parties whose representatives are entitled to participate in the meetings provided for under Article IX so requests by a communication addressed to the depositary Government, a Conference of all the Contracting Parties shall be held as soon as practicable to review the operation of the Treaty.

   b. Any modification or amendment to the present Treaty which is approved at such a Conference by a majority of the Contracting Parties there represented, including a majority of those whose representatives are entitled to participate in the meetings provided for under Article IX, shall be communicated by the depositary Government to all Contracting Parties immediately after the termination of the Conference and shall enter into force in accordance with the provisions of para-graph 1 of the present Article

   c. If any such modification or amendment has not entered into force in accordance with the provisions of subparagraph 1(a) of this Article within a period of two years after the date of its communication to all the Contracting Parties, any Contracting Party may at any time after the expiration of that period give notice to the depositary Government of its withdrawal from the present Treaty; and such withdrawal shall take effect two years after the receipt of the notice by the depositary Government.

Article XIII

1. The present Treaty shall be subject to ratification by the signatory States. It shall be open for accession by any State which is a Member of the United Nations, or by any other State which may be invited to accede to the Treaty with the consent of all the Contracting Parties whose representatives are entitled to participate in the meetings provided for under Article IX of the Treaty.
2. Ratification of or accession to the present Treaty shall be effected by each State in accordance with its constitutional processes.
3. Instruments of ratification and instruments of accession shall be deposited with the Government of the United States of America, hereby designated as the depositary Government.
4. The depositary Government shall inform all signatory and acceding States of the date of each deposit of an instrument of ratification or accession, and the date of entry into force of the Treaty and of any modification or amendment thereto.
5. Upon the deposit of instruments of ratification by all the signatory States, the present Treaty shall enter into force for those States and for States which have deposited instruments of accession. Thereafter the Treaty shall enter into force for any acceding State upon the deposit of its instruments of accession.
6. The present Treaty shall be registered by the depositary Government pursuant to Article 102 of the Charter of the United Nations.

Article XIV

The present Treaty, done in the English, French, Russian and Spanish languages, each version being equally authentic, shall be deposited in the archives of the Government of the United States of America, which shall transmit duly certified copies thereof to the Governments of the signatory and acceding States.

The Antarctic Treaty
signed in Washington on 1 December 1959
entered into force on 23 June 1961

Appendix III: Signatories to the Antarctic Treaty

The Antarctic Treaty was signed in Washington on 1 December 1959 by 12 states, and entered into force for those states on 23 June 1961. Below are listed in chronological order the dates of ratification of the Treaty by the original signatories, the dates of accession or succession by other states, and the dates upon which acceding states became Consultative Parties.

Chronological Order

	State	Date	Status	Date when Acceding State Became Consultative Party
1	United Kingdom	31 May 1960	OS/CP	
2	South Africa	21 June 1960	OS/CP	
3	Belgium	26 July 1960	OS/CP	
4	Japan	4 August 1960	OS/CP	
5	United States of America	18 August 1960	OS/CP	
6	Norway	24 August 1960	OS/CP	
7	France	16 September 1960	OS/CP	
8	New Zealand	1 November 1960	OS/CP	
9	Russia[1]	2 November 1960	OS/CP	
10	Poland	8 June 1961	AS/CP	29 July 1977
11	Argentina	23 June 1961	OS/CP	
12	Australia	23 June 1961	OS/CP	
13	Chile	23 June 1961	OS/CP	
14	Czech Republic[2]	14 June 1962	AS	
15	Slovak Republic[2]	14 June 1952	AS	
16	Denmark	20 May 1965	AS	
17	Netherlands	30 March 1967	AS/CP	19 November 1990
18	Romania	15 September 1971	AS	
	German Democratic Republic[3]	19 November 1974	AS/CP	5 October 1987
19	Brazil	16 May 1975	AS/CP	12 September 1983
20	Bulgaria	11 September 1978	AS/CP	25 May 1998
21	Germany, Federal Republic of	5 February 1979	AS/CP	3 March 1981
22	Uruguay	11 January 1980	AS/CP	7 October 1985
23	Papua New Guinea[4]	16 March 1981	AS	
24	Italy	18 March 1981	AS/CP	5 October 1987
25	Peru	10 April 1981	AS/CP	9 October 1989
26	Spain	31 March 1982	AS/CP	21 September 1988
27	China, People's Republic of	8 June 1983	AS/CP	7 October 1985
28	India	19 August 1983	AS/CP	12 September 1983
29	Hungary	27 January 1984	AS	
30	Sweden	24 April 1984	AS/CP	21 September 1988
31	Finland	15 May 1984	AS/CP	9 October 1989
32	Cuba	16 August 1984	AS	
33	Korea, Republic of	28 November 1986	AS/CP	9 October 1989
34	Greece	8 January 1987	AS	
35	Korea, Democratic People's Republic of	21 January 1987	AS	
36	Austria	25 August 1987	AS	

(Continued)

Chronological Order (Continued)

	State	Date	Status	Date when Acceding State Became Consultative Party
37	Ecuador	15 September 1987	AS/CP	19 November 1990
38	Canada	4 May 1988	AS	
39	Colombia	31 January 1989	AS	
40	Switzerland	15 November 1990	AS	
41	Guatemala	31 July 1991	AS	
42	Ukraine	28 October 1992	AS	
43	Turkey	25 January 1996	AS	
44	Venezuela	24 March 1999	AS	
45	Estonia	17 May 2001	AS	

OS = Original Signatory
CP = Consultative party
AS = Acceding State
Notes:
[1]Known as the Soviet Union until December 1990.
[2]Succeeded to the Treaty as part of Czechoslovakia which separated into two republics on 1 January 1993.
[3]Became united with Federal Republic of Germany on 3 October 1990 (now known as Germany).
[4]Succeeded to the Treaty after independence from Australia.

Alphabetical List of Countries

State	Date	Status	Date when Acceding State Became Consultative Party
Argentina	23 June 1961	OS/CP	
Australia	23 June 1961	OS/CP	
Austria	25 August 1987	AS	
Belgium	26 July 1960	OS/CP	
Brazil	16 May 1975	AS/CP	12 September 1983
Bulgaria	11 September 1978	AS/CP	25 May 1998
Canada	4 May 1988	AS	
Chile	23 June 1961	OS/CP	
China, People's Republic of	8 June 1983	AS/CP	7 October 1985
Colombia	31 January 1989	AS	
Cuba	16 August 1984	AS	
Czech Republic[2]	14 June 1962	AS	
Denmark	20 May 1965	AS	
Ecuador	15 September 1987	AS/CP	19 November 1990
Estonia	17 May 2001	AS	
Finland	15 May 1984	AS/CP	9 October 1989
France	16 September 1960	OS/CP	
German Democratic Republic[3]	19 November 1974	AS/CP	5 October 1987
Germany, Federal Republic of	5 February 1979	AS/CP	3 March 1981
Greece	8 January 1987	AS	
Guatemala	31 July 1991	AS	
Hungary	27 January 1984	AS	
India	19 August 1983	AS/CP	12 September 1983
Italy	18 March 1981	AS/CP	5 October 1987
Japan	4 August 1960	OS/CP	
Korea, Democratic People's Republic of	21 January 1987	AS	
Korea, Republic of	28 November 1986	AS/CP	9 October 1989
Netherlands	30 March 1967	AS/CP	19 November 1990
New Zealand	1 November 1960	OS/CP	

(Continued)

Alphabetical List of Countries (Continued)

State	Date	Status	Date when Acceding State Became Consultative Party
Norway	24 August 1960	OS/CP	
Papua New Guinea[4]	16 March 1981	AS	
Peru	10 April 1981	AS/CP	9 October 1989
Poland	8 June 1961	AS/CP	29 July 1977
Romania	15 September 1971	AS	
Russia[1]	2 November 1960	OS/CP	
Slovak Republic[2]	14 June 1952	AS	
South Africa	21 June 1960	OS/CP	
Spain	31 March 1982	AS/CP	21 September 1988
Sweden	24 April 1984	AS/CP	21 September 1988
Switzerland	15 November 1990	AS	
Turkey	25 January 1996	AS	
Ukraine	28 October 1992	AS	
United Kingdom	31 May 1960	OS/CP	
United States of America	18 August 1960	OS/CP	
Uruguay	11 January 1980	AS/CP	7 October 1985
Venezuela	24 March 1999	AS	

OS = Original Signatory
CP = Consultative party
AS = Acceding State

Notes:

[1]Known as the Soviet Union until December 1990.
[2]Succeeded to the Treaty as part of Czechoslovakia which separated into two republics on 1 January 1993.
[3]Became united with Federal Republic of Germany on 3 October 1990 (now known as Germany).
[4]Succeeded to the Treaty after independence from Australia.

Appendix IV: SCAR Code of Conduct for Use of Animals for Scientific Purposes in Antarctica

Preamble

RECOGNIZING that Man has a moral obligation to respect all animals and to have due consideration for their capacity for suffering and memory:

ACCEPTING nevertheless that Man in his quest for knowledge has a need to use animals where there is a reasonable expectation that the result will provide a significant advance in knowledge or be of overall benefit for animals;

RESOLVED to limit the use of animals for experimental and other scientific purposes, with the aim of replacing such use wherever practical, in particular by seeking alternative measures and encouraging the use of these alternative measures;

DESIRING to adopt common provisions in order to protect animals used in those procedures which may possibly cause pain, suffering, distress or lasting harm and to ensure that where unavoidable they shall be kept to a minimum;

SCAR has adopted a code of conduct which is based on the international guiding principles for biomedical research involving animals as developed by the Council for International Organization of Medical Sciences.

Code of Conduct

I. The advancement of biological knowledge and the development of improved means to the protection of the health and well-being both of man and of the animals require recourse to experimentation on intact live mammals and birds of a wide variety of species.

II. Methods such as mathematical models, computer simulation and *in vitro* biological systems should be used wherever appropriate.

III. Animal experiments should be undertaken only after due consideration of their relevance for human or animal health and the advancement of biological knowledge.

IV. The animals selected for an experiment should be of an appropriate species and quality, and the minimum number required to obtain scientifically valid results.

V. Investigators and other personnel should never fail to treat animals as sentient, and should regard their proper care and use and the avoidance or minimization of discomfort, distress, or pain as ethical imperatives.

VI. Investigators should assume that procedures that would cause pain in human beings cause pain in other mammals and in birds.

VII. Procedures with animals that may cause more than momentary or minimal pain or distress should be performed with appropriate sedation, analgesia, or anesthesia in accordance with accepted veterinary practice. Surgical or other painful procedures should not be performed on unanesthetized animals paralyzed by chemical agents.

VIII. Where waivers are required in relation to the provisions of article VII, the decisions should not rest solely with the investigators directly concerned but should be made, with due regard to the provisions of articles IV, V and VI, by a suitably constituted review body. Such waivers should not be made solely for the purposes of teaching or demonstration.

IX. At the end, or, when appropriate, during an experiment animals that would otherwise suffer severe or chronic pain, distress, discomfort, or disablement that cannot be relieved should be painlessly killed.

X. The best possible living conditions and supervision should be maintained for animals kept for biomedical purposes.

XI. It is the responsibility of the director of an institute or department using animals to ensure that investigators and personnel have appropriate qualifications or experience for conducting procedures on animals. Adequate opportunities shall be provided for in-service training, including the proper and humane concern for the animals under their care.

Appendix V: Protocol on Environmental Protection to the Antarctic Treaty

Preamble

The States Parties to this Protocol to the Antarctic Treaty, hereinafter referred to as the Parties,

Convinced of the need to enhance the protection of the Antarctic environment and dependent and associated ecosystems;

Convinced of the need to strengthen the Antarctic Treaty system so as to ensure that Antarctica shall continue forever to be used exclusively for peaceful purposes and shall not become the scene or object of international discord;

Bearing in mind the special legal and political status of Antarctica and the special responsibility of the Antarctic Treaty Consultative Parties to ensure that all activities in Antarctica are consistent with the purposes and principles of the Antarctic Treaty;

Recalling the designation of Antarctica as a Special Conservation Area and other measures adopted under the Antarctic Treaty system to protect the Antarctic environment and dependent and associated ecosystems;

Acknowledging further the unique opportunities Antarctica offers for scientific monitoring of and research on processes of global as well as regional importance;

Reaffirming the conservation principles of the Convention on the Conservation of Antarctic Marine Living Resources;

Convinced that the development of a comprehensive regime for the protection of the Antarctic environment and dependent and associated ecosystems is in the interest of mankind as a whole;

Desiring to supplement the Antarctic Treaty to this end;

Have agreed as follows:

Article 1

Definitions

For the purposes of this Protocol:

(a) "The Antarctic Treaty" means the Antarctic Treaty done at Washington on 1 December 1959;

(b) "Antarctic Treaty area" means the area to which the provisions of the Antarctic Treaty apply in accordance with Article VI of that Treaty;

(c) "Antarctic Treaty Consultative Meetings" means the meetings referred to in Article IX of the Antarctic Treaty;

(d) "Antarctic Treaty Consultative Parties" means the Contracting Parties to the Antarctic Treaty entitled to appoint representatives to participate in the meetings referred to in Article IX of that Treaty;

(e) "Antarctic Treaty system" means the Antarctic Treaty, the measures in effect under that Treaty, its associated separate international instruments in force and the measures in effect under those instruments;

(f) "Arbitral Tribunal" means the Arbitral Tribunal established in accordance with the Schedule to this Protocol, which forms an integral part thereof;

(g) "Committee" means the Committee for Environmental Protection established in accordance with Article 11.

Article 2

Objective and Designation

The Parties commit themselves to the comprehensive protection of the Antarctic environment and dependent and associated ecosystems and hereby designate Antarctica as a natural reserve, devoted to peace and science.

Article 3

Environmental Principles

1. The protection of the Antarctic environment and dependent and associated ecosystems and the intrinsic value of Antarctica, including its wilderness and aesthetic values and its value as an area for the conduct of scientific research, in particular research essential to understanding the global environment, shall

be fundamental considerations in the planning and conduct of all activities in the Antarctic Treaty area.

2. To this end:

   (a) activities in the Antarctic Treaty area shall be planned and conducted so as to limit adverse impacts on the Antarctic environment and dependent and associated ecosystems;
   (b) activities in the Antarctic Treaty area shall be planned and conducted so as to avoid:

      (i) adverse effects on climate or weather patterns;
      (ii) significant adverse effects on air or water quality;
      (iii) significant changes in the atmospheric, terrestrial (including aquatic), glacial or marine environments;
      (iv) detrimental changes in the distribution, abundance or productivity of species or populations of species of fauna and flora;
      (v) further jeopardy to endangered or threatened species or populations of such species; or
      (vi) degradation of, or substantial risk to, areas of biological, scientific, historic, aesthetic or wilderness significance;

   (c) activities in the Antarctic Treaty area shall be planned and conducted on the basis of information sufficient to allow prior assessments of, and informed judgements about, their possible impacts on the Antarctic environment and dependent and associated ecosystems and on the value of Antarctica for the conduct of scientific research; such judgements shall take account of:

      (i) the scope of the activity, including its area, duration and intensity;
      (ii) the cumulative impacts of the activity, both by itself and in combination with other activities in the Antarctic Treaty area;
      (iii) whether the activity will detrimentally affect any other activity in the Antarctic Treaty area;
      (iv) whether technology and procedures are available to provide for environmentally safe operations;
      (v) whether there exists the capacity to monitor key environmental parameters and ecosystem components so as to identify and provide early warning of any adverse effects of the activity and to provide for such modification of operating procedures as may be necessary in the light of the results of monitoring or increased knowledge of the Antarctic environment and dependent and associated ecosystems; and
      (vi) whether there exists the capacity to respond promptly and effectively to accidents, particularly those with potential environmental effects;

   (d) regular and effective monitoring shall take place to allow assessment of the impacts of ongoing activities, including the verification of predicted impacts;
   (e) regular and effective monitoring shall take place to facilitate early detection of the possible unforeseen effects of activities carried on both within and outside the Antarctic Treaty area on the Antarctic environment and dependent and associated ecosystems.

3. Activities shall be planned and conducted in the Antarctic Treaty area so as to accord priority to scientific research and to preserve the value of Antarctica as an area for the conduct of such research, including research essential to understanding the global environment.
4. Activities undertaken in the Antarctic Treaty area pursuant to scientific research programmes, tourism and all other governmental and non-governmental activities in the Antarctic Treaty area for which advance notice is required in accordance with Article VII (5) of the Antarctic Treaty, including associated logistic support activities, shall:

   (a) take place in a manner consistent with the principles in this Article; and
   (b) be modified, suspended or cancelled if they result in or threaten to result in impacts upon the Antarctic environment or dependent or associated ecosystems inconsistent with those principles.

Article 4

Relationship with the Other Components of the Antarctic Treaty System

1. This Protocol shall supplement the Antarctic Treaty and shall neither modify nor amend that Treaty.

2. Nothing in this Protocol shall derogate from the rights and obligations of the Parties to this Protocol under the other international instruments in force within the Antarctic Treaty system.

Article 5

Consistency with the Other Components of the Antarctic Treaty System

The Parties shall consult and co-operate with the Contracting Parties to the other international instruments in force within the Antarctic Treaty system and their respective institutions with a view to ensuring the achievement of the objectives and principles of this Protocol and avoiding any interference with the achievement of the objectives and principles of those instruments or any inconsistency between the implementation of those instruments and of this Protocol.

Article 6

Co-operation

1. The Parties shall co-operate in the planning and conduct of activities in the Antarctic Treaty area. To this end, each Party shall endeavour to:
   (a) promote co-operative programmes of scientific, technical and educational value, concerning the protection of the Antarctic environment and dependent and associated ecosystems;
   (b) provide appropriate assistance to other Parties in the preparation of environmental impact assessments;
   (c) provide to other Parties upon request information relevant to any potential environmental risk and assistance to minimize the effects of accidents which may damage the Antarctic environment or dependent and associated ecosystems;
   (d) consult with other Parties with regard to the choice of sites for prospective stations and other facilities so as to avoid the cumulative impacts caused by their excessive concentration in any location;
   (e) where appropriate, undertake joint expeditions and share the use of stations and other facilities; and
   (f) carry out such steps as may be agreed upon at Antarctic Treaty Consultative Meetings.
2. Each Party undertakes, to the extent possible, to share information that may be helpful to other Parties in planning and conducting their activities in the Antarctic Treaty area, with a view to the protection of the Antarctic environment and dependent and associated ecosystems.
3. The Parties shall co-operate with those Parties which may exercise jurisdiction in areas adjacent to the Antarctic Treaty area with a view to ensuring that activities in the Antarctic Treaty area do not have adverse environmental impacts on those areas.

Article 7

Prohibition of Mineral Resource Activities

Any activity relating to mineral resources, other than scientific research, shall be prohibited.

Article 8

Environmental Impact Assessment

1. Proposed activities referred to in paragraph 2 below shall be subject to the procedures set out in Annex I for prior assessment of the impacts of those activities on the Antarctic environment or on dependent or associated ecosystems according to whether those activities are identified as having:
   (a) less than a minor or transitory impact;
   (b) a minor transitory impact; or
   (c) more than a minor or transitory impact.
2. Each Party shall ensure that the assessment procedures set out in Annex I are applied in the planning processes leading to decisions about any activities undertaken in the Antarctic Treaty area pursuant to scientific research programmes, tourism and all other governmental and non-governmental activities in the Antarctic Treaty area for which advance notice is required under Article VII (5) of the Antarctic Treaty, including associated logistic support activities.
3. The assessment procedures set out in Annex I shall apply to any change in an activity whether the change arises from an increase or decrease in the intensity of an existing activity,

from the addition of an activity, the decommissioning of a facility, or otherwise.

4. Where activities are planned jointly by more than one Party, the Parties involved shall nominate one of their number to coordinate the implementation of the environmental impact assessment procedures set out in Annex I.

Article 9

Annexes

1. The Annexes to this Protocol shall form an integral part thereof.
2. Annexes, additional to Annexes I-IV, may be adopted and become effective in accordance with Article IX of the Antarctic Treaty.
3. Amendments and modifications to Annexes may be adopted and become effective in accordance with Article IX of the Antarctic Treaty, provided that any Annex may itself make provision for amendments and modifications to become effective on an accelerated basis.
4. Annexes and any amendments and modifications thereto which have become effective in accordance with paragraphs 2 and 3 above shall, unless an Annex itself provides otherwise in respect of the entry into effect of any amendment or modification thereto, become effective for a Contracting Party to the Antarctic Treaty which is not an Antarctic Treaty Consultative Party, or which was not an Antarctic Treaty Consultative Party at the time of the adoption, when notice of approval of that Contracting Party has been received by the Depositary.
5. Annexes shall, except to the extent that an Annex provides otherwise, be subject to the procedures for dispute settlement set out in Articles 18 to 20.

Article 10

Antarctic Treaty Consultative Meetings

1. Antarctic Treaty Consultative Meetings shall, drawing upon the best scientific and technical advice available:

   (a) define, in accordance with the provisions of this Protocol, the general policy for the comprehensive protection of the Antarctic environment and dependent and associated ecosystems; and

   (b) adopt measures under Article IX of the Antarctic Treaty for the implementation of this Protocol.

2. Antarctic Treaty Consultative Meetings shall review the work of the committee and shall draw fully upon its advice and recommendations in carrying out the tasks referred to in paragraph 1 above, as well as upon the advice of the Scientific Committee on Antarctic Research.

Article 11

Committee for Environmental Protection

1. There is hereby established the Committee for Environmental Protection.
2. Each Party shall be entitled to be a member of the Committee and to appoint a representative who may be accompanied by experts and advisers.
3. Observer status in the Committee shall be open to any Contracting Party to the Antarctic Treaty which is not a Party to this Protocol.
4. The Committee shall invite the President of the Scientific Committee on Antarctic Research and the Chairman of the Scientific Committee for the Conservation of Antarctic Marine Living Resources to participate as observers at its sessions. The Committee may also, with the approval of the Antarctic Treaty Consultative Meeting, invite such other relevant scientific, environmental and technical organisations which can contribute to its work to participate as observers at its sessions.
5. The Committee shall present a report on each of its sessions to the Antarctic Treaty Consultative Meeting. The report shall cover all matters considered at the session and shall reflect the views expressed. The report shall be circulated to the Parties and to observers attending the session, and shall thereupon be made publicly available.
6. The Committee shall adopt its rules of procedure which shall be subject to approval by the Antarctic Treaty Consultative Meeting.

Article 12

Functions of the Committee

1. The functions of the Committee shall be to provide advice and formulate recommendations

to the Parties in connection with the implementation of this Protocol, including the operation of its Annexes, for consideration at Antarctic Treaty Consultative Meetings, and to perform such other functions as may be referred to it by the Antarctic Treaty Consultative Meetings. In particular, it shall provide advice on:

(a) the effectiveness of measures taken pursuant to this Protocol;
(b) the need to update, strengthen or otherwise improve such measures;
(c) the need for additional measures, including the need for additional Annexes, where appropriate;
(d) the application and implementation of the environmental impact assessment procedures set out in Article 8 and Annex I;
(e) means of minimising or mitigating environmental impacts of activities in the Antarctic Treaty area;
(f) procedures for situations requiring urgent action, including response action in environmental emergencies;
(g) the operation and further elaboration of the Antarctic Protected Area system;
(h) inspection procedures, including formats for inspection reports and checklists for the conduct of inspections;
(i) the collection, archiving, exchange and evaluation of information related to environmental protection;
(j) the state of the Antarctic environment; and
(k) the need for scientific research, including environmental monitoring, related to the implementation of this Protocol.

2. In carrying out its functions, the Committee shall, as appropriate, consult with the Scientific Committee on Antarctic Research, the Scientific Committee for the Conservation of Antarctic Marine Living Resources and other relevant scientific, environmental and technical organizations.

Article 13

Compliance with This Protocol

1. Each Party shall take appropriate measures within its competence, including the adoption of laws and regulations, administrative actions and enforcement measures, to ensure compliance with this Protocol.
2. Each Party shall exert appropriate efforts, consistent with the Charter of the United Nations, to the end that no one engages in any activity contrary to this Protocol.
3. Each Party shall notify all other Parties of the measures it takes pursuant to paragraphs 1 and 2 above.
4. Each Party shall draw the attention of all other Parties to any activity which in its opinion affects the implementation of the objectives and principles of this Protocol.
5. The Antarctic Treaty Consultative Meetings shall draw the attention of any State which is not a Party to this Protocol to any activity undertaken by that State, its agencies, instrumentalities, natural or juridical persons, ships, aircraft or other means of transport which affects the implementation of the objectives and principles of this Protocol.

Article 14

Inspection

1. In order to promote the protection of the Antarctic environment and dependent and associated ecosystems, and to ensure compliance with this Protocol, the Antarctic Treaty Consultative Parties shall arrange, individually or collectively, for inspections by observers to be made in accordance with Article VII of the Antarctic Treaty.
2. Observers are:

   (a) observers designated by any Antarctic Treaty Consultative Party who shall be nationals of that Party; and
   (b) any observers designated at Antarctic Treaty Consultative Meetings to carry out inspections under procedures to be established by an Antarctic Treaty Consultative Meeting.

3. Parties shall co-operate fully with observers undertaking inspections, and shall ensure that during inspections, observers are given access to all parts of stations, installations, equipment, ships and aircraft open to inspection under Article VII (3) of the Antarctic Treaty, as well as to all records maintained thereon which are called for pursuant to this Protocol.
4. Reports of inspections shall be sent to the Parties whose stations; installations, equipment, ships or aircraft are covered by the

reports. After those Parties have been given the opportunity to comment, the reports and any comments thereon shall be circulated to all the Parties and to the Committee, considered at the next Antarctic Treaty Consultative Meeting, and thereafter made publicly available.

Article 15

Emergency Response Action

1. In order to respond to environmental emergencies in the Antarctic Treaty area, each Party agrees to:

   (a) provide for prompt and effective response action to such emergencies which might arise in the performance of scientific research programmes, tourism and all other governmental and non-governmental activities in the Antarctic Treaty area for which advance notice is required under Article VII (15) of the Antarctic Treaty, including associated logistic support activities; and
   (b) establish contingency plans for response to incidents with potential adverse effects on the Antarctic environment or dependent and associated ecosystems.

2. To this end, the Parties shall:

   (a) co-operate in the formulation and implementation of such contingency plans; and
   (b) establish procedures for immediate notification of, and co-operative response to, environmental emergencies.

3. In the implementation of this Article, the Parties shall draw upon the advice of the appropriate international organisations.

Article 16

Liability
Consistent with the objectives of this Protocol for the comprehensive protection of the Antarctic environment and dependent and associated ecosystems, the Parties undertake to elaborate rules and procedures relating to liability for damage arising from activities taking place in the Antarctic Treaty area and covered by this Protocol. Those rules and procedures shall be included in one or more Annexes to be adopted in accordance with Article 9 (2).

Article 17

Annual Report by Parties

1. Each Party shall report annually on the steps taken to implement this Protocol. Such reports shall include notifications made in accordance with Article 13 (3), contingency plans established in accordance with Article 15 and any other notifications and information called for pursuant to this Protocol for which there is no other provision concerning the circulation and exchange of information.
2. Reports made in accordance with paragraph 1 above shall be circulated to all Parties and to the Committee, considered at the next Antarctic Treaty Consultative Meeting, and made publicly available.

Article 18

Dispute Settlement
If a dispute arises concerning the interpretation or application of this Protocol, the parties to the dispute shall, at the request of any one of them, consult among themselves as soon as possible with a view to having the dispute resolved by negotiation, inquiry, mediation, conciliation, arbitration, judicial settlement or other peaceful means to which the parties to the dispute agree.

Article 19

Choice of Dispute Settlement Procedure

1. Each Party, when signing, ratifying, accepting, approving or acceding to this Protocol, or at any time thereafter, may choose, by written declaration, one or both of the following means for the settlement of disputes concerning the interpretation or application of Articles 7, 8 and 15 and, except to the extent that an Annex provides otherwise, the provisions of any Annex and, insofar as it relates to these Articles and provisions, Article 13:

   (a) the International Court of Justice;
   (b) the Arbitral Tribunal.

2. A declaration made under paragraph 1 above shall not affect the operation of Article 18 and Article 20 (2).
3. A Party which has not made a declaration under paragraph 1 above or in respect of which a declaration is no longer in force shall be deemed to have accepted the competence of the Arbitral Tribunal.
4. If the parties to a dispute have accepted the same means for the settlement of a dispute, the dispute may be submitted only to that procedure, unless the parties otherwise agree.
5. If the parties to a dispute have not accepted the same means for the settlement of a dispute, or if they have both accepted both means, the dispute may be submitted only to the Arbitral Tribunal, unless the parties otherwise agree.
6. A declaration made under paragraph 1 above shall remain in force until it expires in accordance with its terms or until three months after written notice of revocation has been deposited with the Depositary.
7. A new declaration, a notice of revocation or the expiry of a declaration shall not in any way affect proceedings pending before the International Court of Justice or the Arbitral Tribunal, unless the parties to the dispute otherwise agree.
8. Declarations and notices referred to in this Article shall be deposited with the Depositary who shall transmit copies thereof to all Parties.

Article 20

Dispute Settlement Procedure

1. If the parties to a dispute concerning the interpretation or application of Articles 7, 8 or 15 or, except to the extent that an Annex provides otherwise, the provisions of any Annex or, insofar as it relates to these Articles and provisions, Article 13, have not agreed on a means for resolving it within 12 months of the request for consultation pursuant to Article 18, the dispute shall be referred, at the request of any party to the dispute, for settlement in accordance with the procedure determined by Article 19 (4) and (5).
2. The Arbitral Tribunal shall not be competent to decide or rule upon any matter within the scope of Article IV of the Antarctic Treaty. In addition, nothing in this Protocol shall be interpreted as conferring competence or jurisdiction on the International Court of Justice or any other tribunal established for the purpose of settling disputes between Parties to decide or otherwise rule upon any matter within the scope of Article IV of the Antarctic Treaty.

Article 21

Signature

This Protocol shall be open for signature at Madrid on the 4th of October 1991 and thereafter at Washington until the 3rd of October 1992 by any State which is a Contracting Party to the Antarctic Treaty.

Article 22

Ratification, Acceptance, Approval or Accession

1. This Protocol is subject to ratification, acceptance of approval by signatory States.
2. After the 3rd of October 1992 this Protocol shall be open for accession by any State which is a Contracting Party to the Antarctic Treaty.
3. Instruments of ratification, acceptance, approval or accession shall be deposited with the Government of the United States of America, hereby designated as the Depositary.
4. After the date on which this Protocol has entered into force, the Antarctic Treaty Consultative Parties shall not act upon a notification regarding the entitlement of a Contracting Party to the Antarctic Treaty to appoint representatives to participate in Antarctic Treaty Consultative Meetings in accordance with Article IX (2) of the Antarctic Treaty unless that Contracting Party has first ratified, accepted, approved or acceded to this Protocol.

Article 23

Entry into Force

1. This Protocol shall enter into force on the thirtieth day following the date of deposit of instruments of ratification, acceptance, approval or accession by all States which are Antarctic Treaty Consultative Parties at the date on which this Protocol is adopted.

2. For each Contracting Party to the Antarctic Treaty which, subsequent to the date of entry into force of this Protocol, deposits an instrument of ratification, acceptance, approval or accession, this Protocol shall enter into force on the thirtieth day following such deposit.

Article 24

Reservations

Reservations to this Protocol shall not be permitted.

Article 25

Modification or Amendment

1. Without prejudice to the provisions of Article 9, this Protocol may be modified or amended at any time in accordance with the procedures set forth in Article XII (1) (a) and (b) of the Antarctic Treaty.
2. If, after the expiration of 50 years from the date of entry into force of this Protocol, any of the Antarctic Treaty Consultative Parties so requests by a communication addressed to the Depositary, a conference shall be held as soon as practicable to review the operation of this Protocol.
3. A modification or amendment proposed at any Review Conference called pursuant to paragraph 2 above shall be adopted by a majority of the Parties, including ¾ of the States which are Antarctic Treaty Consultative Parties at the time of adoption of this Protocol.
4. A modification or amendment adopted pursuant to paragraph 3 above shall enter into force upon ratification, acceptance, approval or accession by ¾ of the Antarctic Treaty Consultative Parties, including ratification, acceptance, approval or accession by all States which are Antarctic Treaty Consultative Parties at the time of adoption of this Protocol.
5. (a) With respect to Article 7, the prohibition on Antarctic mineral resource activities contained therein shall continue unless there is in force a binding legal regime on Antarctic mineral resource activities that includes an agreed means for determining whether, and, if so, under which conditions, any such activities would be acceptable. This regime shall fully safeguard the interests of all States referred to in Article IV of the Antarctic Treaty and apply the principles thereof. Therefore, if a modification or amendment to Article 7 is proposed at a Review Conference referred to in paragraph 2 above, it shall include such a binding legal regime.
   (b) If any such modification or amendment has not entered into force within 3 years of the date of its adoption, any Party may at any time thereafter notify to the Depositary of its withdrawal from this Protocol, and such withdrawal shall take effect 2 years after receipt of the notification by the Depositary.

Article 26

Notifications by the Depositary

The Depositary shall notify all Contracting Parties to the Antarctic Treaty of the following:

(a) signatures of this Protocol and the deposit of instruments of ratification, acceptance, approval or accession;
(b) the date of entry into force of this Protocol and any additional Annex thereto;
(c) the date of entry into force of any amendment or modification to this Protocol;
(d) the deposit of declarations and notices pursuant to Article 19; and
(e) any notification received pursuant to Article 25 (5) (b).

Article 27

Authentic Texts and Registration with the United Nations

1. This Protocol, done in the English, French, Russian and Spanish languages, each version being equally authentic, shall be deposited in the archives of the Government of the United States of America, which shall transmit duly certified copies thereof to all Contracting Parties to the Antarctic Treaty.
2. This Protocol shall be registered by the Depositary pursuant to Article 102 of the charter of the United Nations.

Additional texts

Schedule to the Protocol: Arbitration

Annex I: Environmental Impact Assessment
Annex II: Conservation of Antarctic Fauna and Flora
Annex III: Waste Disposal and Waste Management
Annex IV: Prevention of Marine Pollution
Annex V: Area Protection and Management
Annex VI: Liability for Environmental Emergencies

Note: The complete text of the Protocol on Environmental Protection to the Antarctic Treaty is reproduced here. In addition, there is a "Schedule to the Protocol," and there are six annexes that are listed at the end. The full texts of the "Schedule" and the annexes may be seen at: http://ww.cep.aq/default.asap?casid=5074

Appendix VI: Scientific Research Stations in the Antarctic Region

Austral Winter 2005

1	Amundsen-Scott	United States	89°59′51″ S	139°16′22″ E
2	Troll	Norway	72°00′07″ S	02°32′02″ E
3	Maitri	India	70°45′57″ S	11°44′09″ E
4	Novolazarevskaya	Russia	70°46′26″ S	11°51′54″ E
5	*Marion Island	South Africa	46°52′34″ S	37°51′32″ E
6	Syowa	Japan	69°00′25″ S	39°35′01″ E
7	Molodezhnaya	Russia	67°40′18″ S	45°51′21″ E
8	*Alfred Faure, Îles Crozet	France	46°25′48″ S	51°51′40″ E
9	Mawson	Australia	67°36′17″ S	62°52′15″ E
10	*Port aux Français, Îles Kerguelen	France	49°21′05″ S	70°12′20″ E
11	Zhongshan	China	69°22′16″ S	76°23′13″ E
12	Progress	Russia	69°22′44″ S	76°23′13″ E
13	*Martin de Viviès, Île Amsterdam	France	37°49′48″ S	77°34′12″ E
14	Davis	Australia	68°34′38″ S	77°58′21″ E
15	Mirny	Russia	66°33′07″ S	93°00′53″ E
16	Vostok	Russia	78°28′00″ S	106°48′00″ E
17	Casey	Australia	66°17′00″ S	110°31′11″ E
18	Concordia	France/Italy	72°06′06″ S	123°23′43″ E
19	Dumont d'Urville	France	66°39′46″ S	140°00′05″ E
20	*Macquarie Island	Australia	54°29′58″ S	158°56′09″ E
21	McMurdo	United States	77°50′53″ S	166°40′06″ E
22	Scott Base	New Zealand	77°51′00″ S	166°45′46″ E
23	Rothera	United Kingdom	67°34′10″ S	68°07′12″ W
24	San Martin	Argentina	68°07′47″ S	67°06′12″ W
25	Vernadsky	Ukraine	65°14′43″ S	64°15′24″ W
26	Palmer	United States	64°46′30″ S	64°03′04″ W
27	Capitan Arturo Prat	Chile	62°30′00″ S	59°41′00″ W
28	†Presidente Eduardo Frei	Chile	62°12′00″ S	58°57′51″ W
29	†Escudero	Chile	62°12′04″ S	58°57′45″ W
30	†Great Wall	China	62°12′59″ S	58°57′44″ W
31	†Bellingshausen	Russia	62°11′47″ S	58°57′39″ W
32	†Artigas	Uruguay	62°11′04″ S	58°54′09″ W
33	†King Sejong	Korea	62°13′24″ S	58°47′21″ W
34	†Jubany	Argentina	62°14′16″ S	58°39′52″ W
35	†Arctowski	Poland	62°09′34″ S	58°28′15″ W
36	†Comandante Ferraz	Brazil	62°05′00″ S	58°23′28″ W
37	General Bernardo O'Higgins	Chile	63°19′15″ S	57°54′01″ W
38	Esperanza	Argentina	63°23′42″ S	56°59′46″ W
39	Marambio	Argentina	64°14′42″ S	56°39′25″ W
40	Orcadas	Argentina	60°44′20″ S	44°44′17″ W
41	*Bird Island	United Kingdom	54°00′31″ S	38°03′08″ W
42	*King Edward Point	United Kingdom	54°17′00″ S	36°29′37″ W
43	Belgrano II	Argentina	77°52′29″ S	34°37′37″ W
44	Halley	United Kingdom	75°34′54″ S	26°32′28″ W
45	*Gough Island	South Africa	40°21′56″ S	09°52′00″ W
46	Neumayer	Germany	70°38′00″ S	08°15′48″ W
47	SANAE	South Africa	71°40′25″ S	02°49′44″ W

*Stations north of 60° S
†Stations on King George Island

Appendix VII: Antarctic Academic Journals

Analysis of the *Antarctic Bibliography* shows that scientific papers on Antarctica are now published in more than one thousand journals. There are few journals devoted entirely to the polar regions and only six—*Antarctic Science, Antarctic Research Series, Antarctic Record, CCAMLR Science, Terra Antartica,* and *Byuleten' Ukrains'kogo Antarktichnogo Tsentru*—are committed just to the continent and its surrounding seas.

Bipolar journals include *Polar Biology* and *Polarforschung* from Germany, *Polar Record* from the UK, *Arctic Antarctic and Alpine Research* from the United States, and journals from China and Poland.

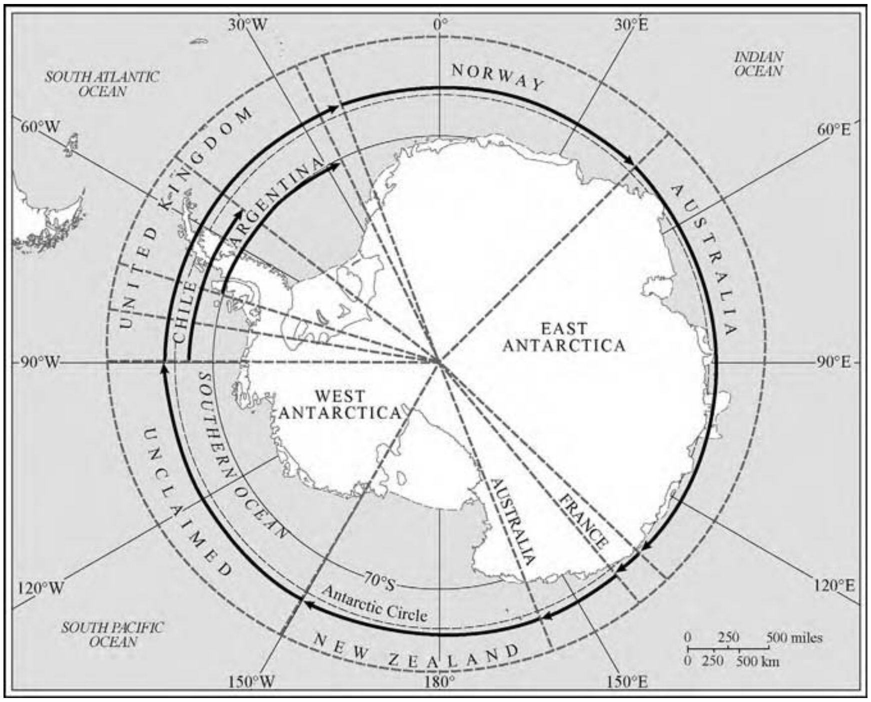
The most significant disciplinary journals for Antarctic science include *Journal of Geophysical Research, Geophysical Research Letters, Deep Sea Research, Annals of Glaciology,* as well as *Nature* and *Science*.

The top twenty-two journals, in terms of the numbers of Antarctic science papers published over the last 6 years, are (in alphabetical order):

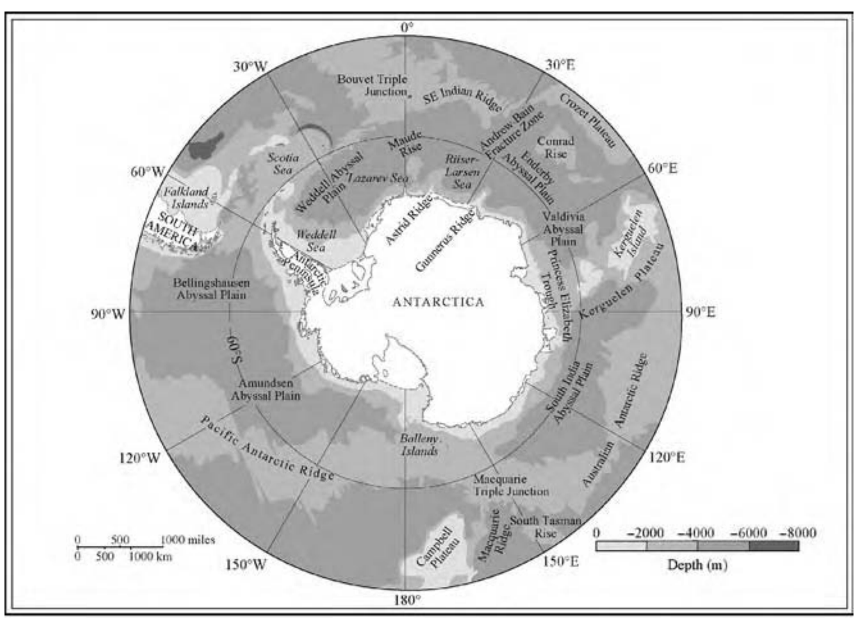
Antarctic Research Series
Antarctic Science
Berichte zur Polar- und Meeresforschung (formerly Berichte zur Polarforschung)
Bulletin—Royal Society of New Zealand
Byuleten' Ukrains'kogo Antarktichnogo Tsentru
Chinese Journal of Polar Science
Deep-Sea Research. Parts I and II
Geografiska Annaler. Series A: Physical Geography
Geophysical Research Letters
Global and Planetary Change
Jidi Yanjiu = Chinese Journal of Polar Research
Journal of Climate
Journal of Geophysical Research
Journal of Glaciology
Nankyoku Shiryo = Antarctic Record
Nature
Polar Biology
Polish Polar Research
Science
Terra Antartica
Terra Antartica Reports

D. W. H. Walton

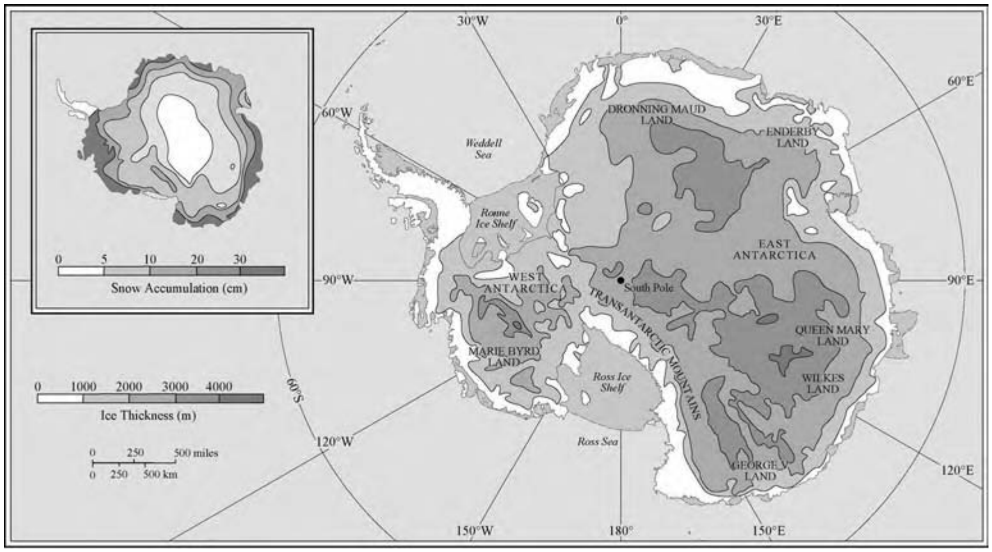
Maps



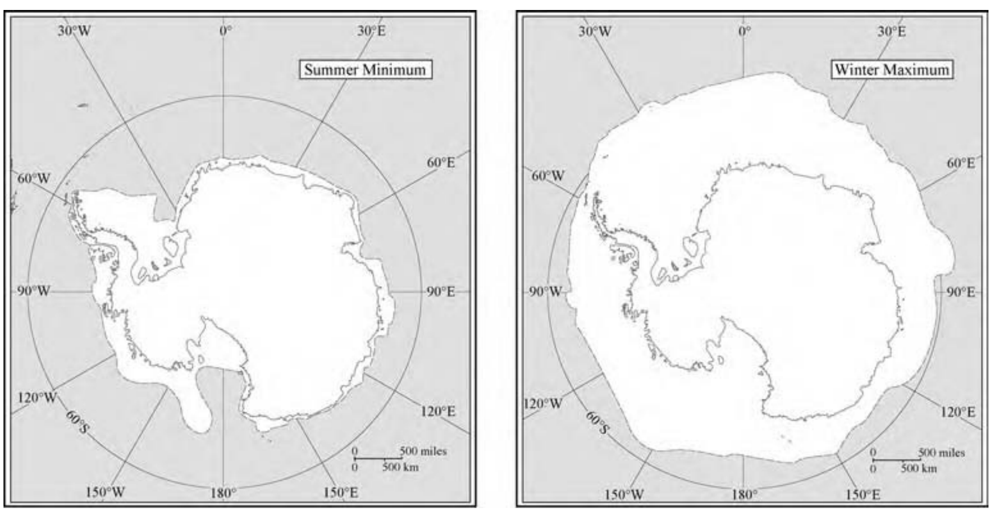
Antarctic territorial claims.



Bathymetry of the Southern Ocean region. The Southern Ocean is delineated by the 60° S latitude and the Antarctic coast. Depths are color-coded according to the scale bar at the base of the figure, with contours drawn at 2000 m intervals.

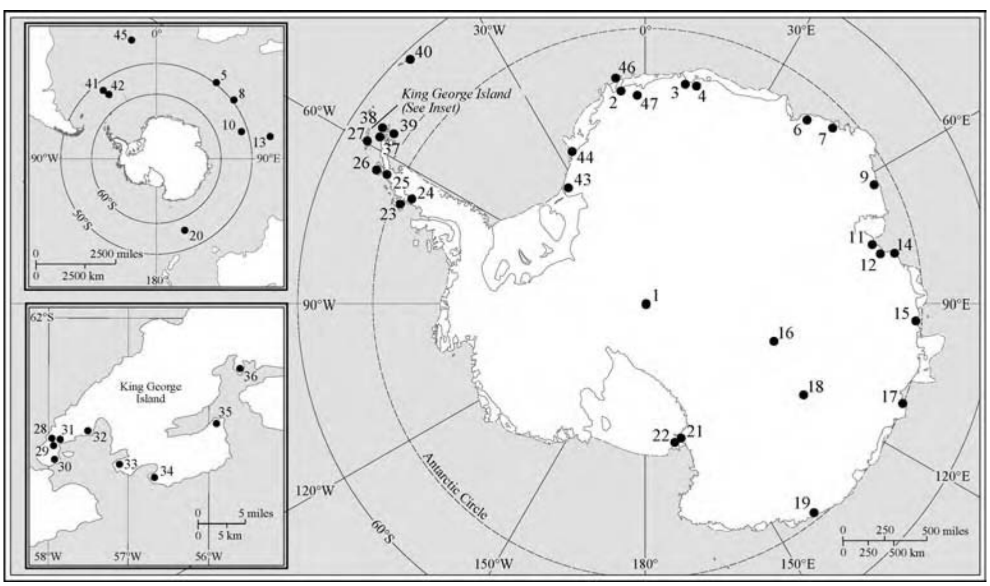


Antarctic ice sheet thickness and mean annual snow accumulation. Note that the areas of greatest ice thickness are not the same as those of maximum snow accumulation.

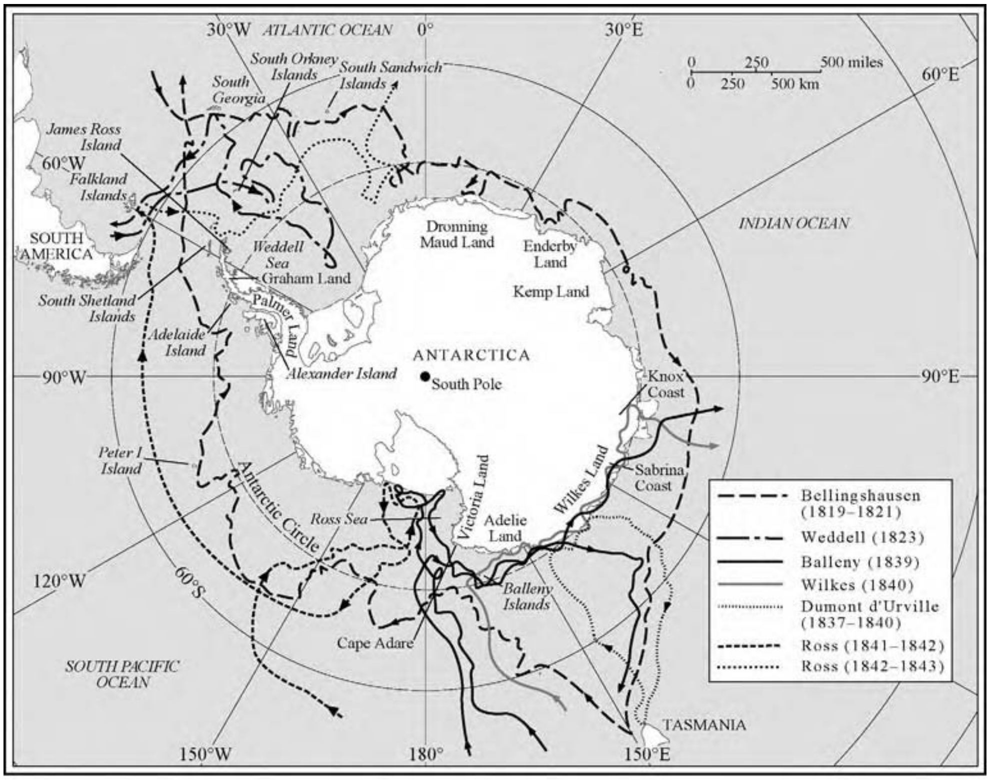


Sea ice extent. Left: minimum, during February, when only the Weddell, Bellingshausen, and Amundsen seas have much ice cover. Right: maximum, during September, when the ice cover increases at least five times over its minimum.

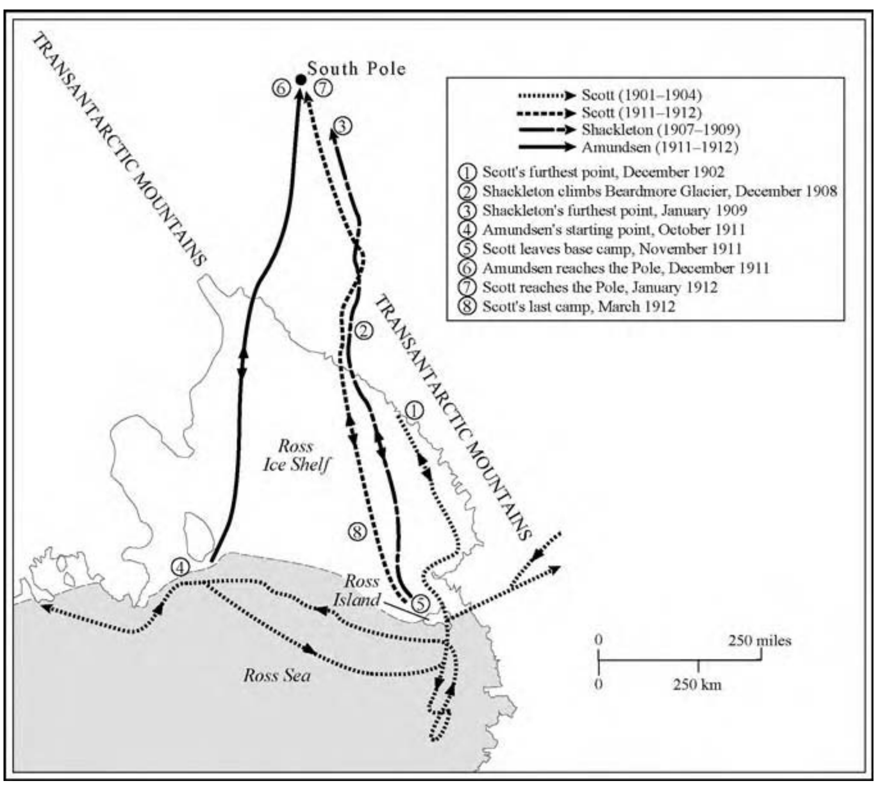
The Antarctic Plate. The continent sits well in the middle of it, surrounded by five other plates.



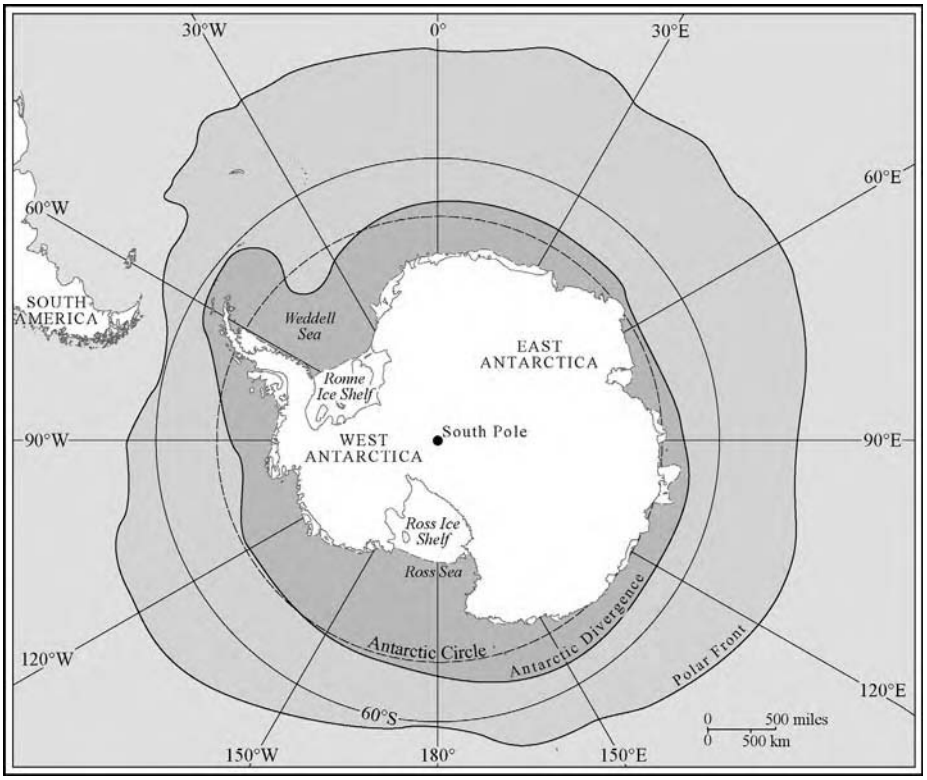
Scientific research stations in the Antarctic, austral winter 2005. Information about the numbered bases can be found in Appendix VI.



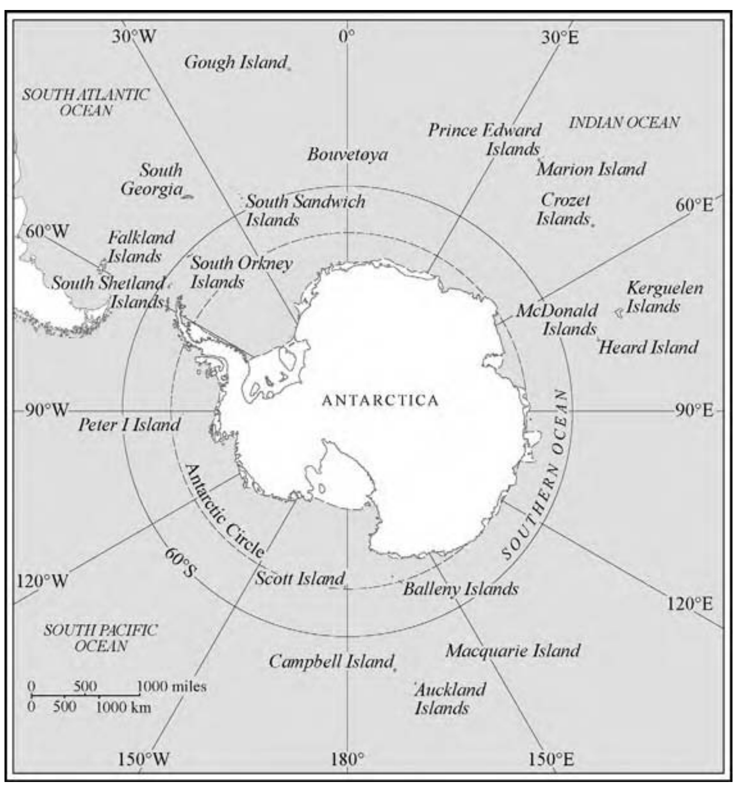
The maritime routes of Antarctic expeditions in the first half of the nineteenth century.



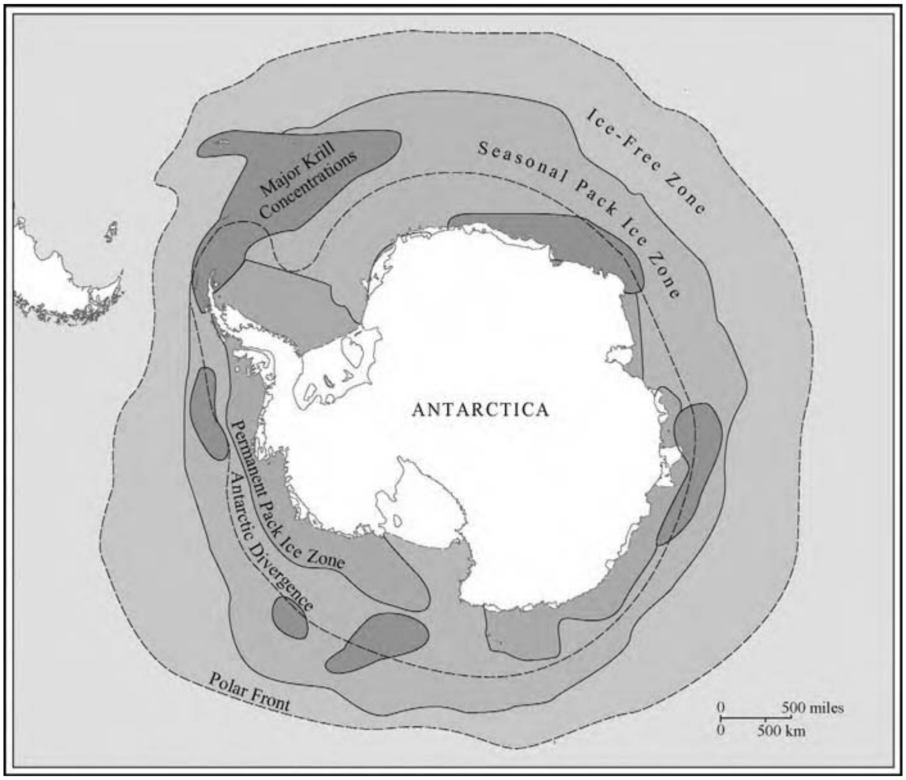
The race for the South Pole.



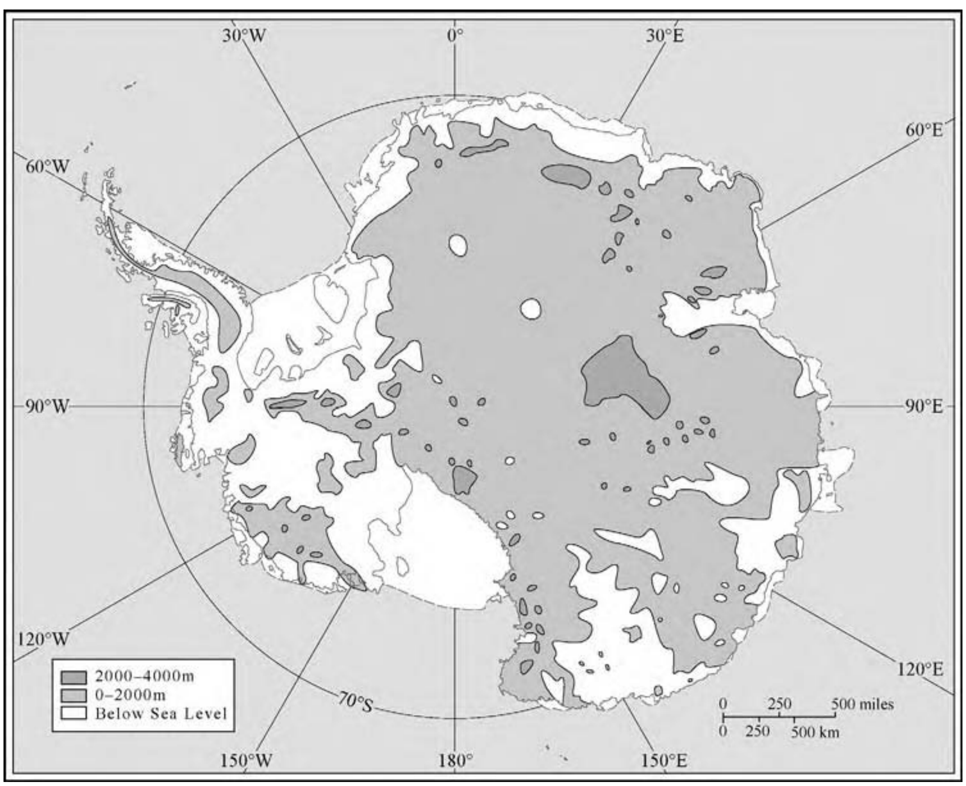
The major oceanographic fronts: the Polar Front (formerly the Antarctic Convergence) and the Antarctic Divergence.



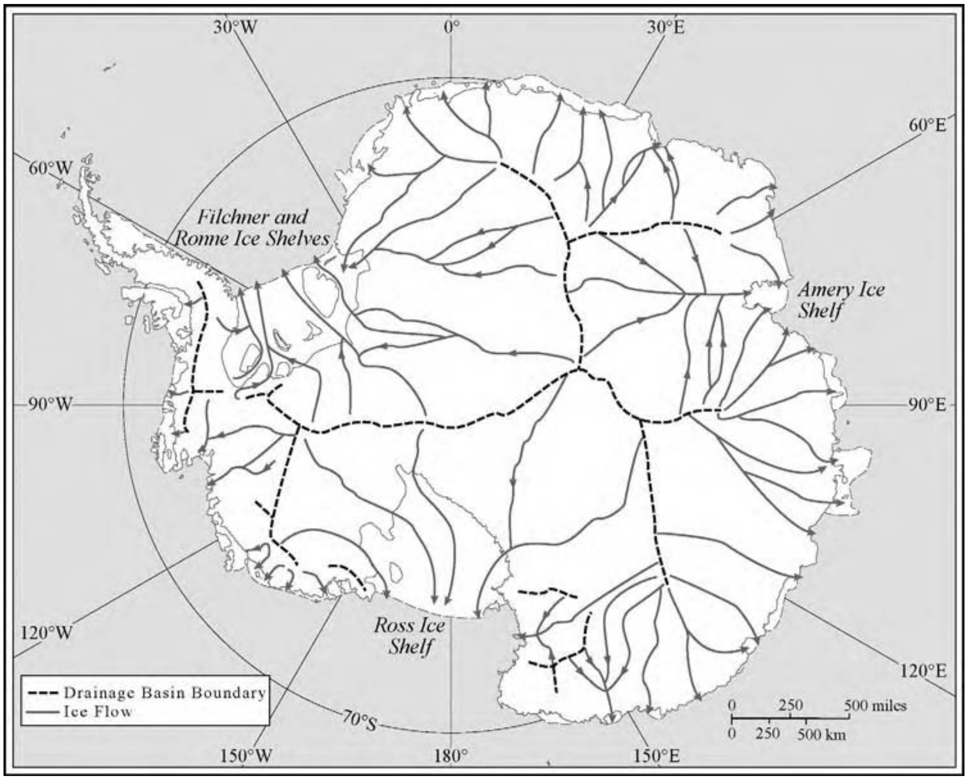
The sub-Antarctic islands.



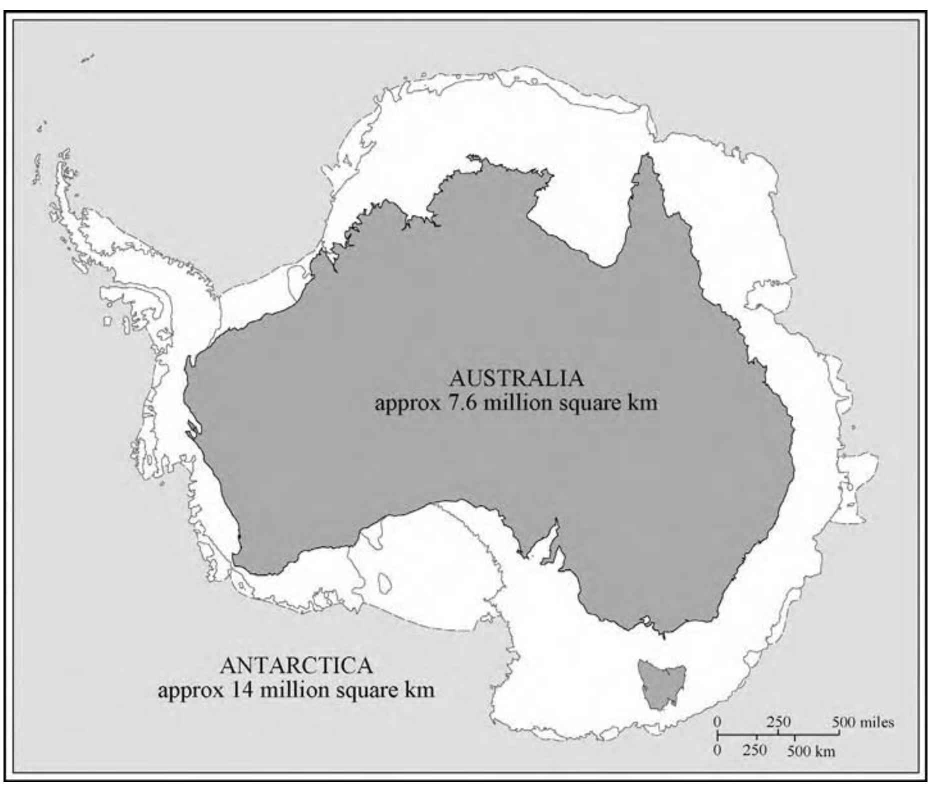
Krill abundance in the Southern Ocean. The major concentrations of krill occur within the seasonal pack ice zone.



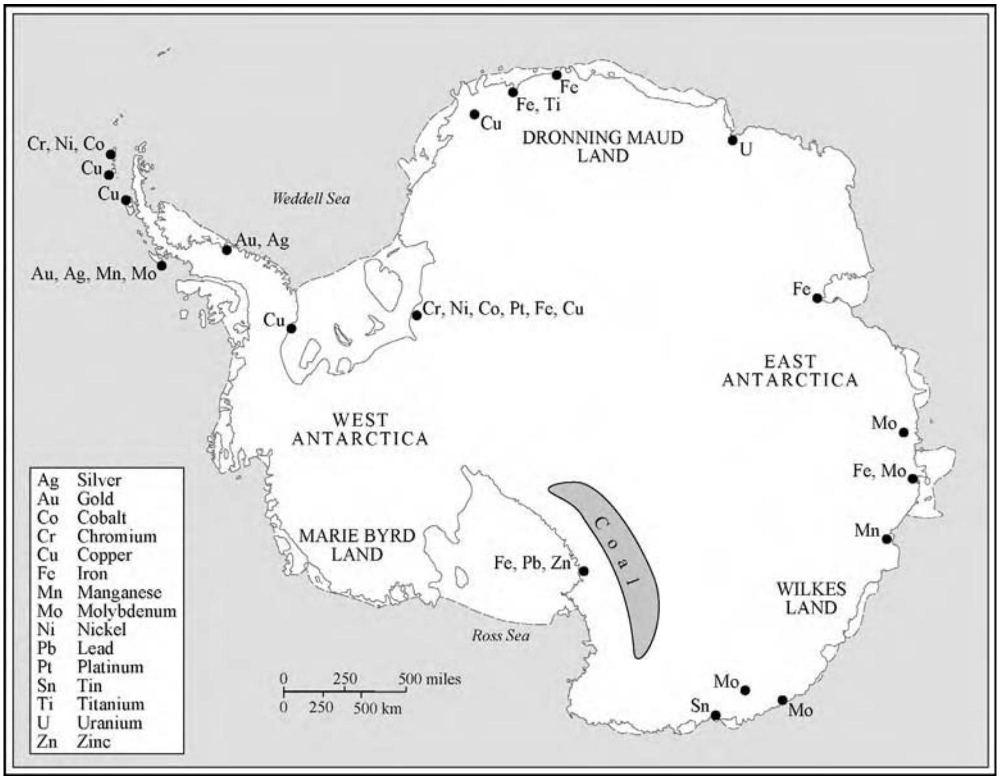
Bedrock of continental Antarctica, as it would be if the overlying ice were removed and isostatic rebound had caused it to rise.



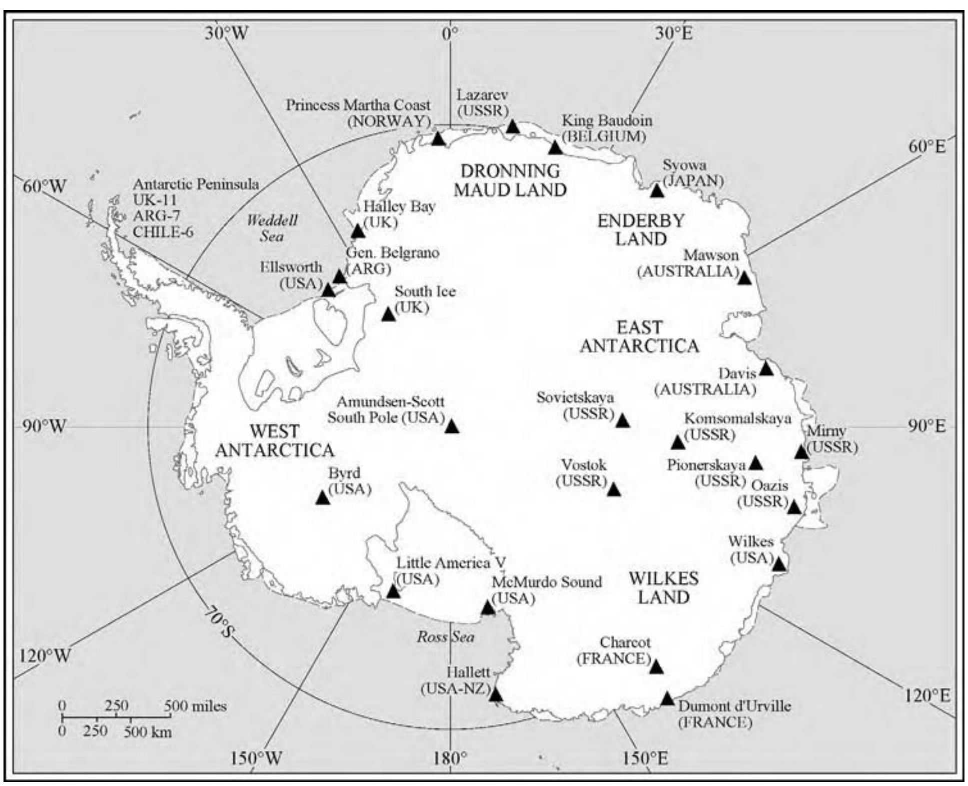
The movement of the Antarctic Ice Sheet as it flows downhill towards the coast through drainage basins. There are three major drainage areas—forming the Ross Ice Shelf, the Filchner-Ronne Ice Shelf, and the Amery Ice Shelf—as well as other areas around the entire continent.



The continent of Antarctica is almost twice as large as Australia. The size of the former is approximately 14 million square km, while of the latter approximately 7.6 million square km.



Minerals found in the Antarctic. Most of these are inaccessible.



Stations of the International Geophysical Year. A dozen different nations set up 50 different stations for the largest scientific project ever undertaken. Many of these stations or successors at the same locations are still in use today.

Index

A

INDEX

B

C

D

E

F

G

H

I

J

K

M

O

X

Y

Z

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