direction of upper-air winds and tracked by a radio direction-finding instrument or radar.

Salinity An expression of the mass of dissolved solids in sea water per unit mass.

Thermohaline circulation That part of the ocean circulation which is due to density differences. Density differences arise from temperature (thermo) and salinity (haline) differences which occur throughout the oceans due to varying patterns of heating, cooling, evaporation, and precipitation.

Water mass Body of water which is identified by a certain set of property characteristics (i.e., not by topographic boundaries). These properties are most often temperature, salinity, and oxygen and nutrient concentrations.

Wind-driven circulation That part of the ocean circulation which is driven by the winds. The wind acts as a frictional force on the sea surface. As the wind transfers its energy to the ocean it can not only create waves, but it can also create surface currents. The convergence and divergence of these currents can in turn create regions of upwelling deep waters and downwelling surface waters.

See also

Ekman Transport and Pumping. Heat and Momentum Fluxes at the Sea Surface. Thermohaline Circulation. Wind Driven Circulation.

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HEAVY METALS

See **TRANSITION METALS AND HEAVY METAL SPECIATION**

HISTORY OF OCEAN SCIENCES

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Oceanography is the scientific study of the ocean, its inhabitants, and its physical and chemical conditions. Since its emergence as a recognized scientific discipline, oceanography has been characterized less by the intellectual cohesiveness of a traditional academic discipline than by multidisciplinary, often large-scale, investigation of a complex and forbidding environment. The term 'oceanography' was not applied until the 1880s, at which point it still competed with such alternatives as 'thassalography' and 'oceanology'. In many countries, 'oceanography' now encompasses both biological and physical traditions, but this meaning is not universal. In Russia, for instance, it does not include biological sciences; the umbrella term remains 'oceanology'.

Before scientists studied the ocean as a geographic place with an integrated ecosystem, they addressed individual biological, physical, and chemical questions related to the sea. European expansion promoted the study of marine phenomena, initiating a lasting link between commercial interests and oceanography. Institutional interest in the sea by the Royal Society in London flourished briefly from 1660 to 1675, when members, including Robert Hooke and Robert Boyle, discussed marine research, developed instruments to make observations at sea, and conducted experiments on sea water to discover its physical and chemical properties. Sailors and travelers continued to make scattered observations at sea, working from the research plan and equipment established by the Society. In addition, tidal studies were prosecuted consistently from the late seventeenth century to well into the nineteenth.

Following decades of quiescence, a renewal of interest in marine phenomena occurred in the mid-eighteenth century. As part of that century's growth of astronomy, geophysics, chemistry, geology, and meteorology, investigators began making observations at sea as part of their scientific pursuit of other fields. Initially, observers were traveling gentlemen, naturalists, or eclipse-expedition astronomers; later they were scientific explorers. Beginning with the voyages of Captain James Cook in the last third of the century, British exploration became characterized by attention to scientific observations. The amount of energy devoted to marine science depended on the level of interest of expedition leaders or individual members, but, in the last quarter of the century, the volume of experiments and observations made at sea increased. Virtually all ocean investigation during this time focused on temperature and salinity of water, reflecting the growth of chemical sciences. The concept of oceanic circulation sustained by differences in density, which was widely discussed in the early nineteenth century, emerged at this time. The study of waves became more important while marine natural history remained at a modest level.

Early in the nineteenth century the emphasis on physical and chemical studies continued. Curtailed exploration due to the American Revolutionary War and the Napoleonic Wars slowed work in marine science until another period of rapid expansion between 1815 and 1830. Work then focused largely on currents and salinity, reflecting the fact that marine science was conducted on Arctic expeditions which searched for sperm whaling grounds and the North-west Passage. Navigation and the pursuit of whales prompted Arctic explorers to investigate water temperature and pressure at depths. Enthusiastic individuals, most frequently ships' captains such as William Scorseby, continued to carry on observation programs at sea, but the 1830s saw a decrease of interest in marine science by physical scientists, who turned to rival fields of discovery including meteorology and terrestrial magnetism. At this time, however, British zoologists directed particular attention to marine fauna, embarking on small boats and yachts to collect with modified oyster dredges. Pursuit of new species as well as living relatives of fossilized ones inspired naturalists to reach deeper and deeper into the sea.

Beginning in the 1850s, both British and American hydrographic institutions began deep sea sounding experiments which were guided by the promise of submarine telegraphy, although initiated in support of whaling and navigational concerns. The decades after 1840 saw the gradual awareness by scientists, sailors, entrepreneurs, and governments that the ocean's depths were commercially and intellectually important places to investigate. An unprecedented increase in popular awareness of the sea accompanied this trend. Prefaced by the rage for seaside vacations which was initiated by railroad access to beaches, cultural interest in the ocean was manifested by the popularity of marine natural history collecting and the new maritime novels as well as the vogue for yachting and the personal experiences of growing numbers of ocean travelers and emigrants. Submarine telegraphy and public interest in maritime issues helped scientists argue successfully for government funding of oceanographic voyages. Declining fisheries emphasized the need to know more about the biology of the seas.

Until 1840, Britain led marine science, although important work was conducted by investigators in other countries, especially Scandinavian countries. In Norway, for example, G. O. Sars carried out important research for fisheries and also studied unusual creatures dredged from very deep water. American marine science began to threaten British dominance after mid-century. Matthew Fontaine Maury was the first investigator to compile wind, current, and whale charts to improve navigation and commerce. He also dispatched the first trans-Atlantic sounding voyages in the early 1850s. Under Alexander Dallas Bache's tenure, the US Coast Survey began to include, alongside routine charting work, special studies such as detailed surveys of the Gulf Stream, microscopic examinations of bottom sediments, and dredging cruises with the renowned zoologist Louis Agassiz and his son Alexander. Spencer F. Baird, Secretary of the Smithsonian Institution and United States Fish Commissioner, oversaw American efforts to study marine fauna. In Britain, while physical work was undertaken by the Hydrographic Office and Admiralty exploring expeditions, marine biological science centered around the British Association for the Advancement of Science Dredging Committee from 1839 until the mid-1860s. After that time, a Royal Society–Admiralty partnership took the lead and dispatched a series of summer expeditions. These culminated in the famous four-year circumnavigation of HMS *Challenger* (1872–1876), the first expedition sent out with a mandate to study the world's oceans. The United States, Britain, and other nations as well, quickly followed the example of the Naples Zoological Station and set up coastal marine biological laboratories in the 1880s and 1890s.

In the last quarter of the nineteenth century, many nations sponsored oceanographic voyages modeled after that of *Challenger*. The United States, Russia, Germany, Norway, France, and Italy contributed to the effort to define the limits and contents of the oceans. Late in the nineteenth century, however, the Scandinavian countries promoted a new style of ocean science to replace the great voyage tradition. Mounting concerns about depleted fisheries inspired national efforts in many countries to study the biology of fish species as well as their migration. Sweden initiated the formation of what became in 1902 the International Council for the Exploration of the Seas (ICES), which coordinated research undertaken by eight northern European member nations. Although not a member, the United States also continued active biological research. Victor Henson's discovery of plankton and efforts to quantify its distribution and the subsequent realization of how to use physical oceanography to investigate the movements of fish populations gave oceanographers confidence with which to study the ocean as an undivided system.

World War I disrupted the international community of oceanographers but provided the impetus for developing echo-sounding technology for submarine detection, which had been pioneered for ice detection partly in response to the *Titanic* disaster. By the late 1920s, echo-sounders revolutionized the study of underwater topography and helped scientists to recognize the rift valleys of midocean ridges, showing them to be active, unstable regions. Fishermen took up this technology for locating schools of pelagic fish; later scientists adapted echo-sounding to create fishery-independent surveying tools. Although government funding of oceanographic research dropped back almost to pre-war levels, the late 1920s saw the appearance of the first oceanographic institutions, sponsored mostly by foundations and private individuals. In the United States, the Scripps Institution changed its mission from biological research to oceanography in 1925 and, five years later, the Woods Hole Oceanographic Institution was established on the Atlantic. The availability of ocean-going vessels in the 1930s spurred development of American oceanography on a new scale. Fisheries research, which blossomed in Europe in the 1930s, included important theoretical advances which provided the foundation for later fish population dynamics modeling as well as open ocean research such as Sir Alister Hardy's Continuous Plankton Recorder surveys and Johannes Schmidt's publicly acclaimed search for the mid-Atlantic spawning ground of the European eel. Economic depression affected practical government science, such as fisheries research, as well as private projects, such as several of Schmidt's voyages, which were sponsored by the Carlsberg Foundation. As a consequence, oceanographic work, which was particularly expensive, slowed down dramatically until preparations began for World War II.

As with other sciences, World War II partnerships helped forge a new relationship between governments and oceanography. Oceanographic work during and after the war carried the imprint of wartime government support and policy in both its problem selection and its scale. Physical studies gained and maintained precedence over biological ones. The areas of inquiry promoted by wartime efforts related to submarine and antisubmarine tactics. New research began on underwater acoustics, and ocean floor sediment charts were compiled from existing data. Wave studies also received precedence for their value in predicting surf conditions for landings. After the war, oceanographers and academic institutions, newly accustomed to generous funding, learned to accept and even encourage government support. The foundation of the National Science Foundation, which became the major federal supporter of marine science in the USA, exemplified the new high levels of support for this technology-intensive science. Oceanography became characterized by large-scale, expensive research projects such as the 1960s deep-sea drilling by proponents of the theory of seafloor spreading. Major international projects also became an integral part of ocean sciences, in conjunction with postwar internationalization of science and other sectors. The International Indian Ocean Expedition, for example, targeted the least well-studied of the world's oceans.

By 1950 physical oceanographers were aware of the wanderings of the Gulf Stream and pressed urgently for systematic exploration of ocean variability. Development of deep ocean mooring technology provided the opportunity to study currents and temperatures continuously. This work showed that mesoscale variability was important and was incorporated into general circulation models. Progress in postwar physical oceanography in general proceeded in step with technological improvements, particularly the development of computing power. Another example, that of radioactive tracers and 'experiments' of atomic bomb-testing at sea, led to an intensification of research into biogeochemical cycling from the 1950s. Through programs such as the Geochemical Ocean Sections Study (GEOSECS), tracer use permitted estimates of mixing and circulation times by the late 1960s and led to programs such as the World Ocean Circulation Experiment (WOCE). Circulation and diffusion studies took on renewed importance as public concern about pollution rose. The idea that it was necessary to understand how the ocean functioned in order to avoid inadvertently destroying it fanned development of biological and chemical oceanography from the late 1960s onward. Much effort was funneled into baseline surveying and monitoring programs, initially focusing on potential threats to human health through eating poisoned seafood but soon broadening to investigations of biological effects of contaminants. The fast growth of mariculture from this period also encouraged these studies.

Although many oceanographers became interested in open ocean research and theoretical modeling in the postwar period, some in Europe resuscitated efforts, begun within ICES in the 1930s, to integrate hydrographic knowledge with fisheries biology. This work encompassed the practical attempt to guide fishermen to catch more fish as well as the scientific project of trying to relate recruitment fluctuations to environmental factors. Parallel efforts in the United States bore fruit in the California Cooperative Oceanic Fisheries Investigations (CalCOFI), a cooperative government and academic program which investigated causes for the decline of the California coastal sardine fishery. CalCOFI, though, was an exceptional project; in general through the 1960s little significant intellectual exchange occurred between biological oceanography and fisheries science. Within biological oceanography, the legacy of E. Steeman-Nielsen's radioactive carbon tracer method led to active work measuring primary productivity, with global estimates by J. H. Ryther and others in the late 1960s.

Discovery of high biological diversity in the deep sea in the late 1960s led to work which was considerably enhanced by deep-diving submersibles, whose use dramatically changed our perception of the ocean's depths. In the area of marine geology and geophysics, the two greatest achievements since World War II have been the development of the theory of plate tectonics and the deciphering of Earth's paleoclimate record from deep-sea sediments. The first of these was set in motion by the Vine and Matthews hypothesis of 1963, which rocked the scientific community but was accepted with remarkable speed. Research submersibles played a central role in proving the theory of seafloor spreading. The 1979 discovery of hydrothermal vents, made in the process of these geophysical investigations, led to the surprise discovery of chemosynthetic ecosystems. Reconstruction of Earth's paleoclimates, which became possible due to the large accumulation of data and the availability of deep sea cores from the ocean drilling projects, was fueled by growing scientific concerns about global climate change. This work began during the 1960s with C. David Keeling's launch of time-series measurements of carbon dioxide, which provided the data documenting the increase of atmospheric carbon dioxide attributable to human activities and prompted inquiry into the magnitude of exchange of carbon dioxide between the atmosphere and oceans. Studies of the ocean's role in global warming and weather production have grown in importance in recent years.

Accompanying the rise of the environmental movement, oceanography's multi-faceted attempt to understand the oceans as integrated biological and physical environments made it a compelling discipline to ecologically and environmentally minded scientists from the 1970s onward. Food web investigations became prominent, including those which used mesoscale enclosures such as one designed and run at Canada's Pacific Biological Station in Nanaimo. Discovery of the microbial character of the pelagic food web added a new dimension to biological oceanography. New understanding of production, including a distinction between recycled nutrients and new production made by Dugdale and Goering in 1967, provided biological oceanography with the mathematical formalism for rigorous, quantitative modeling of ocean productivity and biogeochemical fluxes. Modeling capability encouraged a link to be forged between physical and biological oceanography, because new concepts required that physical processes of mixing and upwelling be integrated into ecosystem models dealing with new production, fish production, or export of organic material from the surface layer. The international Global Ocean Ecosystem Dynamics program and the recent resurgence of fisheries oceanography exemplify relatively successful efforts to bridge trophic levels, from plankton to marine mammals and sea birds, and thereby study the ecosystem as a whole.

See also

Continuous Plankton Recorders. Fisheries and Climate. International Organizations. Law of the Sea. Maritime Archaeology. Primary Production Distribution. Primary Production Methods. Primary Production Processes.

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HOLOCENE CLIMATE VARIABILITY

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Introduction

Until a few decades ago it was generally thought that significant large-scale global and regional climate changes occurred at a gradual pace within a timescale of many centuries or millennia. Climate change was assumed to be scarcely perceptible during a human lifetime. The tendency for climate to change abruptly has been one of the most surprising outcomes of the study of Earth history. In particular, paleoceanographic records demonstrate that our present interglacial, the Holocene (the last ~10 000 years), has not been as climatically stable as first thought. It has been suggested that Holocene climate is dominated by millennial-scale variability, with some authorities suggesting that this is a 1500 year cyclicity. These pronounced Holocene climate changes can occur extremely rapidly, within a few centuries or even within a few decades, and involve regional-scale changes in mean annual temperature of several degrees Celsius. In addition, many of these Holocene climate changes are stepwise in nature and may be due to thresholds in the climate system.

Holocene decadal-scale transitions would presumably have been quite noticeable to ancient civilizations. For instance, the emergence of crop agriculture in the Middle East corresponds very closely with a sudden warming event marking the beginning of the Holocene, and the widespread collapse of the first urban civilizations, such as the Old Kingdom in Egypt and the Akkadian Empire, coincided with a cooling event at around 4300 BP. In addition, paleo-records from the late Holocene demonstrate the possible influence of climate change on the collapse of the Mayan civilization (Classic Period), while Andean ice core records suggests that alternating wet and dry periods influenced the rise and fall of coastal and highland cultures of Ecuador and Peru.

It would be foolhardy not to bear in mind such sudden stepwise climate transitions when considering the effects that humans might have upon the present climate system, via the rapid generation of greenhouse gases for instance. Judging by what we have already learnt from Holocene records, it is not improbable that the system may gradually build up over hundreds of years to a 'breaking point' or threshold, after which some dramatic change in the system occurs over just a decade or two. At the threshold point, the climate system is in a delicate and somewhat critical state. It may take only a relatively minor 'adjustment' to trigger the transition and tip the system into abrupt change.

This article summarizes the current paleoceanographic records of Holocene climate variability and the current theories for their causes. Concentrating on records that cover a significant portion of the Holocene. The discussion is limited to centennial–millennial-scale variations. **Figure 1** illustrates the Holocene and its climate variability in context of