off rather than cut, the discarded bands may encircle marine mammals or large fish and become progressively tighter as the animal grows. They also entangle limbs, jaws, heads etc. and affect the animal's ability to move or eat. Plastic straps for four- or six-packs of cans or bottles can affect smaller animals in a similar way.

Miscellaneous other debris This covers a wide variety of materials including plastic bags or sheeting, packing material, plastic waste materials and containers for beverages and other liquids. There are numerous studies of turtles, whales and other marine mammals that were apparently killed by ingesting plastic bags or sheeting. Turtles appear particularly vulnerable to this type of pollution, perhaps by mistaking it for their normal food, e.g. jellyfish. A potentially more serious problem may be the increasing quantities of small plastic particles widely found in the ocean, probably from plastics production and insulation and packing materials. The principal impacts of this material are via ingestion affecting animals' feeding digestion processes. These plastic particles have been found in 25% of the world's sea bird species in one study and up to 90% of the chicks of a single species in another study.

See also

Anti-fouling Materials. Pollution Control. Benthic Organisms Overview. Pollution: Effects on Marine Communities. International Organizations. Law of the Sea. Marine Mammal Overview. Marine Policy Overview. Seabirds as Indicators of Ocean Pollution.

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POLYNYAS

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doi:10.1006/rwos.2001.0007

Introduction

Polynyas are large, persistent regions of open water and thin ice that occur within much thicker pack ice, at locations where climatologically, thick pack ice would be expected. Polynyas have a rectangular or oval aspect ratio with length scales of order 100 km; they persist with intermittent openings and closings at the same location for up to several months, and recur over many years. In contrast to polynyas, leads – another open water feature – are long, linear transient features associated with the pack ice deformation, are not restricted to a particular location, and generally have a much smaller area than polynyas. Polynyas occur in both winter and summer. Given that their physical behavior in winter is more complicated than in summer, we begin with the winter case, then follow with a shorter description of their transition to summer.

Polynyas can be classified into coastal and open-ocean polynyas. Coastal polynyas form where the winter winds advect the adjacent pack ice away from the coast, so that sea water at temperatures close to the freezing point is directly exposed to a large negative heat flux, with the resultant rapid formation of new ice. This new ice is advected away from the coast as fast as it forms. For these polynyas, a typical alongshore length is 100–500 km; a typical offshore length 10–100 km. In contrast, the less common open-ocean polynyas have characteristic diameters of 100 km and are driven by the upwelling of warm ocean water, which maintains a large opening in the pack ice. Because the atmospheric heat loss from the open-ocean polynyas goes into cooling of the water column, they are sometimes called 'sensible heat' polynyas; because the heat loss from coastal polynyas goes into ice growth, they are called 'latent heat' polynyas. Finally, some polynyas, notably the North Water polynya in Baffin Bay, are maintained by both upwelling and ice advection.

Figure 1 shows the locations of some of these polynyas for both hemispheres. In the Northern Hemisphere, most of the polynyas are coastal, with the Kashevarov Bank polynya in the Okhotsk Sea being the only purely open-ocean polynya. The largest coastal polynyas occur in the marginal seas, where the adjacent ice edge provides room for ice divergence; this means that large polynyas occur in the Bering, Okhotsk, and Barents Seas. In the Barents Sea, prominent polynyas occur around Novaya Zemlya, Franz Josef Land, and at occasional coastal sites in the Barents and adjacent Kara Seas. In the Laptev Sea, polynyas occur in early winter along Severnaya Zemlya. There is also a long flaw lead, sometimes referred to as a polynya, which occurs between the shorefast and the pack ice north of the Laptev River delta.

In the vicinity of the Bering Strait, polynyas occur in the Chukchi, Beaufort, and Bering Seas. In the Chukchi Sea, an important polynya occurs along the Alaskan coast; in the Beaufort Sea, polynyas form in early winter along the Alaskan coast and in Amundsen Gulf. In the Bering Sea, large polynyas occur along the Alaskan coast and south of the islands, where the most investigated of these occurs south of St. Lawrence Island. Prominent polynyas also occur along the Siberian coast south of the Bering Strait and in Anadyr Gulf. The Canadian islands are also sites of several polynyas, the largest and most studied being the North Water polynya in Baffin Bay. In north-east Greenland, the North-east Water (NEW) polynya is large in summer, and has also been the subject of a recent field study. Finally, the Okhotsk Sea with the adjacent Tatarskiy Strait is the site of several coastal polynyas and the open-ocean Kashevarov polynya. The Kashevarov polynya occurs over the 200 m deep Kashevarov Bank, where the turbulence associated with a strong tidal resonance generates a heat flux to the surface that creates a region of reduced ice cover with a characteristic diameter of about 100 km.

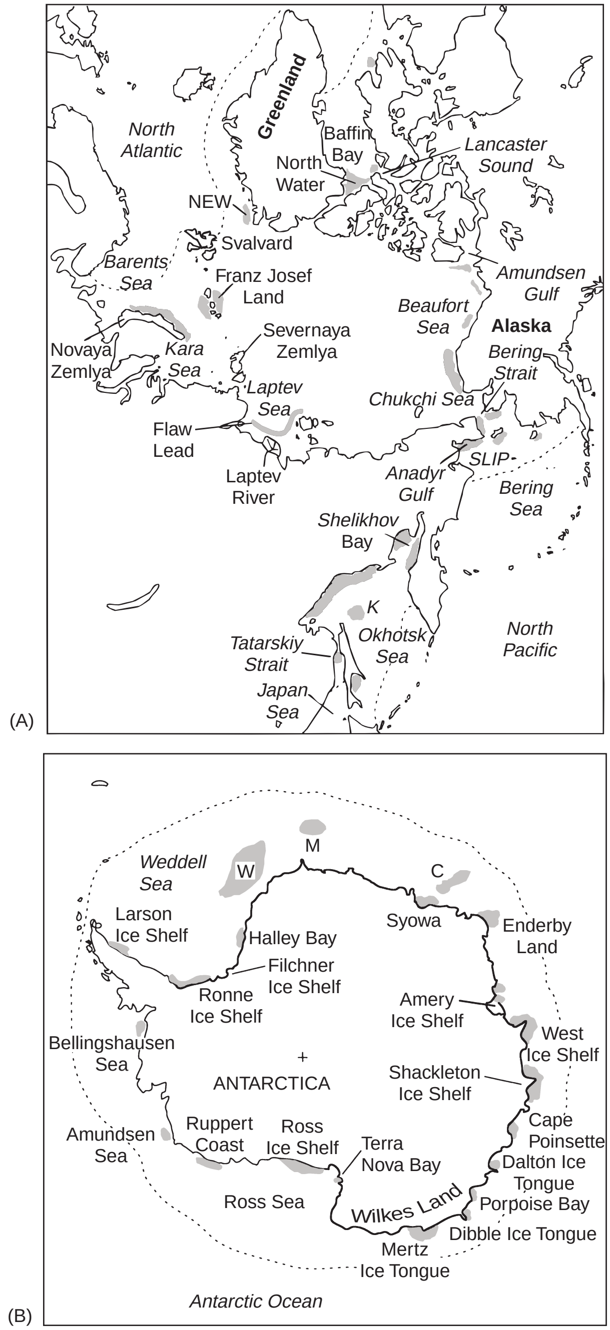

Figure 1 Geographic distribution of polynyas. (A) The Arctic, where SLIP is the St. Lawrence Island Polynya, NEW is the North-east Water, and K is the Kashevarov Bank polynya. (B) The Antarctic, where W is the Weddell polynya, M is the Maud Rise polynya and C is the Cosmonaut Sea polynya. On both figures the dashed line indicates the position of the maximum ice edge. Polar stereographic map projection courtesy of the National Snow and Ice Data Center (NSIDC).

The Southern Hemisphere is characterized by many coastal polynyas and by two or three open-ocean polynyas. The open-ocean polynyas include the Weddell Sea polynya, which only occurred in the 1970s, and the smaller Maud Rise and Cosmonaut Sea polynyas. The coastal polynyas occur at different locations along the Ronne, Amery, and Ross Ice Shelves, where the Ross polynya has recently been studied, and at many locations along the coast. The coastal polynyas form in the lee of headlands, islands, ice shelves, and grounded icebergs and downwind of ice tongues such as the Mertz, Dibble, and Dalton tongues, which extend as much as 100 km off the coast. These polynyas are created by a combination of the dominant easterly winds and the very cold powerful katabatic winds that sweep down the glacial drainage basins and across the pack ice for a few kilometers before slowing. The response to these winds is a series of large polynyas; for example, the overwinter average area of the Mertz Ice Tongue polynya is about 20 000 km^2. Given the prevalence of coastal polynyas compared with mid-ocean polynyas, most of the water mass modification takes place in the former.

Although these polynyas occupy only a small fraction of the areal winter pack ice extent, because the polar pack ice is a good insulator, very large atmospheric heat losses occur from both polynya types. Given these heat losses, the coastal polynyas are regions where large amounts of ice are generated, the ocean is cooled and salt is added to the underlying waters, while the open-ocean polynyas cool the upwelled water, and in the Southern Ocean are suspected to contribute to modification of the Antarctic Bottom Water. As winter progresses into spring, the polynya regions remain important. Because the predominant winds sweep the polynyas free of ice, their ice cover at the end of winter consists of either open water or thin ice. This means that as spring approaches, when the air temperature rises above freezing and the incident solar radiation increases, the polynya ice is either swept away without replacement, or melts away faster than the surrounding pack ice. In the Okhotsk and Bering Seas, for example, the onset of open water in spring occurs both from melting at the offshore ice edge, and from the disappearance of ice at the coastal polynya sites. Because the other Arctic and Antarctic coastal polynyas behave similarly, the coastal polynyas become seasonally open approximately one month earlier than the interior pack. The open ocean polynyas, such as the Kashevarov, Maud, and Cosmonaut, also serve as regions for initiation of the spring melt. As is shown below, the early spring melt of the coastal polynyas has biological consequences.

Physical Processes within the Two Polynya Types

Coastal Polynyas

Because of their relative accessibility and more frequent occurrence, we know much more about coastal than about open-ocean polynyas. **Figure 2**, a schematic drawing of a coastal polynya, shows that as the winds advect the pack ice away from the coast, open water is exposed to the cold winds. This generates a wind-wave field on the open water surface, where the wave amplitudes and wavelengths increase away from the coast. As the polynya width increases, and if the wind speed is greater than about 5–10 $m\,s^{-1}$, the interaction of the waves with the wind stress creates Langmuir circulation within the water column. This circulation consists of rotating vortices with the rotor axes approximately parallel to the surface winds, where adjacent rotors turn in opposite directions and the rotor diameter is approximately equal to either the bottom depth in well-mixed waters or to the halocline depth. Because of the wave and Langmuir mixing, the initial ice formation occurs as follows. If the sea water temperature is above freezing, the combination of

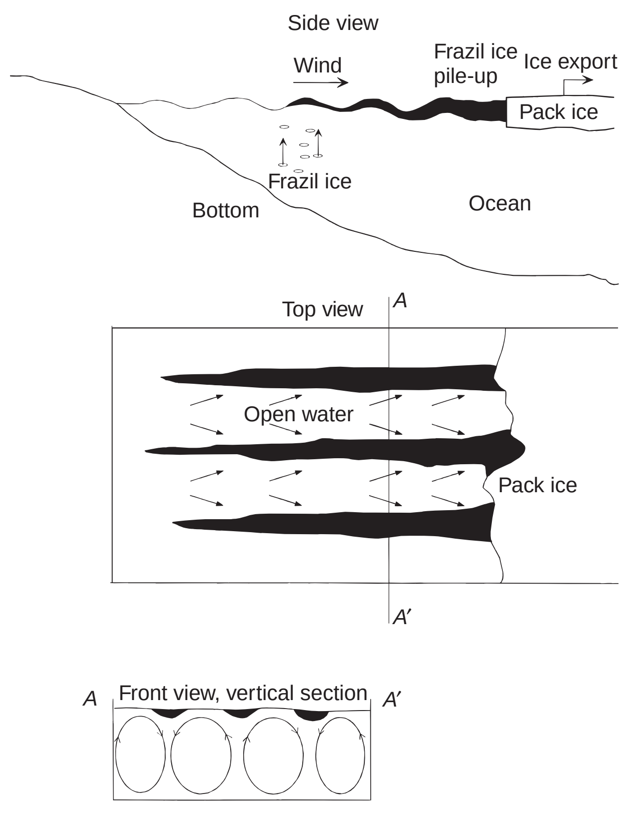

Figure 2 A schematic drawing of a coastal polynya and top and vertical views.

the surface heat loss with the mixing cools the entire column to the freezing point, and sometimes even causes a slight supercooling. This means that once freezing begins, ice formation occurs throughout the water column as small millimeter-scale crystals, called frazil crystals, which float slowly to the surface. As the crystals form, they reject salt to the underlying water column, leading to an oceanic brine flux.

Once these crystals reach the surface, the circulation herds them into slurries taking the form of long bands or plumes of floating ice crystals located at the Langmuir convergence zones. The slurries have thicknesses of order 10 cm, are highly viscous, and damp out the incident short waves. This damping gives the slurries a greasy appearance, so that following old whaling terminology, they are sometimes called grease ice. As the plumes grow downwind, they become wider and increase in thickness. As their thicknesses increase, their surface begins to freeze. The longer ocean swell propagating through the ice, breaks the surface ice into floes with diameters of 0.3 to 0.5 m, called pancake ice. Because of wave-induced collisions, the swell also causes the growth of raised rims around the pancakes, which increase both the wind-drag on the ice and the radar reflectivity. As these ice growth processes proceed, the ice is advected downwind by the wind stress, where it piles up against the edge of the solid pack ice. As time goes on, the width of this region of piled-up ice grows slowly upwind. As an example, **Figure 3** shows a 100 m resolution RADARSAT image of the St. Lawrence Island polynya. The figure shows the region of open water and Langmuir plumes surrounded by pack ice south of the island, where the plumes are approximately parallel to the wind, and the polynya area is about 5000 km^2. Within the plumes, the figure also shows the downwind increase in brightness associated with the growth of pancake ice.

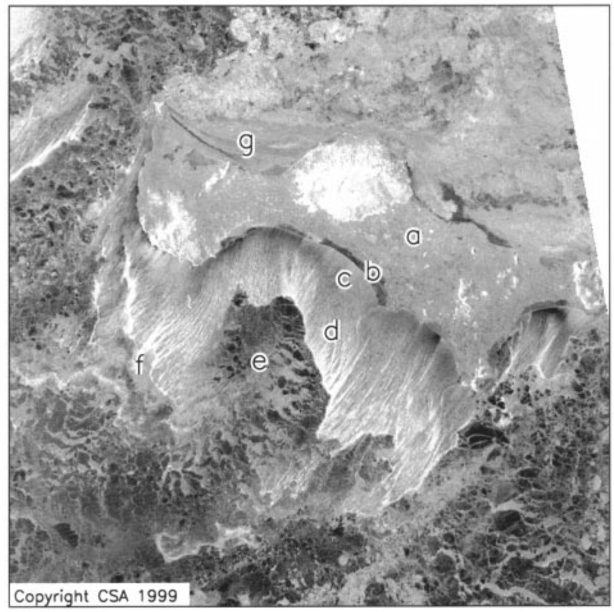

Figure 3 A RADARSAT image of the St. Lawrence Island polynya on 9 January 1999. The length of the island is approximately 150 km. On the image, (a) is the island, (b) is the fast ice south of the island, (c) is open water, (d) is the Langmuir plumes, (e) is the pack ice, (f) is the piled-up grease ice, and (g) is the thick first-year ice north of the island. The wind is blowing from top right to bottom left. Image courtesy of the Alaska SAR Facility, with processing courtesy Harry Stern and copyright the Canadian Space Agency, 1999.

If the wind speeds are slow enough that the Langmuir circulation either does not occur or is not strong enough to circulate the ice crystals the polynya behavior is less well understood. Observations suggest that the downwind transport of ice continues to occur, but with either frazil or thin ice forming immediately adjacent to the coast. Given the offshore transport of ice in both the Langmuir and non-Langmuir cases, the question arises of what determines the winter polynya size. The crosswind polynya scale is set by the coastline configuration over which the ice divergence occurs. The downwind scale is set by a balance between the production of new ice within the polynya, its export downwind to the pack ice edge, and the subsequent upwind growth of the piled up new ice. All else remaining constant, a greater polynya area leads to more ice production and a faster upwind growth of the new ice. An equilibrium size occurs when the retreat of the pack ice edge equals the advance of the piled-up new ice. This balance between production and advection sets the polynya offshore length scale, typically 10–100 km. When the winds stop, the export stops, and the frazil ice freezes into a solid ice cover. For the same wind speed, very cold temperatures yield smaller polynyas because the ice production is so much greater; relatively warm temperatures correspond to large polynyas with less ice production.

Open-ocean Polynyas

The open-ocean polynyas generally occur away from the coast, and are driven by the upwelling of warm sea water (**Figure 4**). In the Northern Hemisphere, the Kashevarov polynya is driven by a tidal resonance, and the North Water and NEW are maintained by a combination of wind-induced ice advection and oceanic upwelling. In the Southern Hemisphere, there have been three open-ocean polynyas. The most famous, intriguing, and mysterious

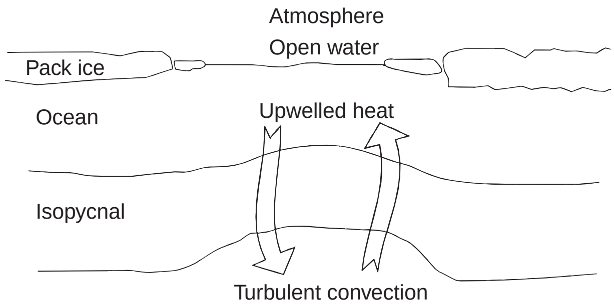

Figure 4 A schematic drawing of an open-ocean polynya, showing mean circulation and mixing.

of these occurred in the Weddell Sea during 1973–76, and was only observed by remote sensing. The Weddell polynya had an open water and thin ice area of about $2\text{–}3 \times 10^5\,\text{km}^2$, which is about the area of Oregon, USA. Because this polynya first occurred over Maud Rise, its subsequent evolution may have been caused by a large eddy that separated from the rise and migrated westward across the Weddell Sea. For the other open-ocean polynyas, both the Cosmonaut and Maud polynyas have maximum areas of about $10^5\,\text{km}^2$. These occur in oceanic regions with large reservoirs of relatively warm water just beneath a weak pycnocline, where upwelling brings the warm water to the surface. These polynyas are self-maintaining, in that as heat is lost to the atmosphere, the surface water becomes denser and sinks, generating a turbulent convection which brings warm deep water to the surface. The convection ceases when the atmosphere warms in spring, or if sufficient fresh water, either produced locally by melting, or advected into the region, places a low-salinity cap on the convection.

Remote Sensing Observations

Even though polynyas were probably first observed by Native American whalers and hunters, our detailed knowledge of their location and variability comes from satellite observations. In the 1970s and early 1980s, the forerunners of the AVHRR (Advanced Very High Resolution Radiometer) instrument provided 1 km resolution visible and thermal imagery of polynyas, but only under cloud-free conditions. Passive microwave instruments such as the SMMR (Scanning Multichannel Microwave Radiometer), which operated between 1978 and 1987, and the SSM/I (Special Sensor Microwave/Imager, operating between 1987 and the present, made it possible to obtain cloud-independent low-resolution imagery of the entire polar pack at intervals of every other day for the SMMR and daily intervals for the SSM/I. These observations led to the discovery of all of the mid-ocean polynyas, and many of the coastal polynyas, and provided time series of their area versus time. The major problem with the SMMR and SMM/I is their low spatial resolution; the 37 GHz SSM/I channel has a 25 km resolution, and the more water vapor-sensitive channel at 85 GHz has a 12.5 km resolution. The planned AMSR (Advanced Microwave Scanning Radiometer), which is scheduled for launch in 2000, has twice the resolution of the SSM/I and should greatly improve our polynya studies. The high-resolution active microwave satellite instruments that are just beginning to be used in polynya research include the 100–500 km swath width synthetic aperture radars (SAR) with their approximately 3-day repeat cycle, and resolutions of 12.5–100 m (**Figure 3**).

Physical Importance

The physical importance of the coastal polynyas is that, because the new ice is being constantly swept away, the polynyas serve as large heat sources to the atmosphere, and as powerful ice and brine factories. For example, while a typical Bering Sea ice thickness is about 0.5 m, the seasonal ice growth in the St. Lawrence polynya is about 5 m, or an order of magnitude greater. Combined with the persistent north-easterly winds, this means that the Bering ice cover can be approximated as a conveyor belt, where the ice forms in the coastal polynyas, then is advected to the ice edge where it melts. This simple conveyor-belt model may also apply to the ice covers of the Weddell and Okhotsk Seas. The brine generated by the polynyas also contributes to the oceanic water masses. The large shallow continental shelves where most of the Arctic coastal polynyas occur provide a dynamic constraint on the brine-generated dense water that permits its density and volume to increase. Because of this constraint, when the dense water eventually drains off the shelves into the deeper basins, it is dense enough to contribute to the intermediate and deep water masses. In this way, the polynyas in the Chukchi, Bering, Beaufort, and Barents Sea polynyas contribute to the cold halocline layer of the Arctic Ocean. (The Bering Sea dense water is transported through the Bering Strait into the Arctic by the pressure difference between the Bering Sea and the Arctic Ocean.) In the Okhotsk Sea, the polynya water contributes to the Okhotsk Intermediate Water and to the North Pacific Intermediate Water. The dynamics and fate of this dense water are topics of current scientific investigation.

In the Antarctic, estimates of the polynya ice growth rates are 0.1–0.2 m d^{-1}, or about 10 m per season. Although the Antarctic shelves are not as broad as the Arctic shelves, the Antarctic coastal polynyas also generate dense shelf water. The drainage of this water contributes to the Antarctic bottom water in the western Weddell Sea, the Ross Sea, and along the Wilkes Land Coast. In the Weddell Sea, the dense water flows beneath the Filchner-Ronne Ice Shelf, causing melting of the glacial ice, and creating a lower-salinity form of the bottom water. The Antarctic open-ocean polynyas cool the warm upwelled deep ocean water, which leads to modification of the intermediate-depth water into cold bottom water.

The Arctic polynyas also contribute to sediment transport. Because freezing occurs at all depths during the initiation of ice formation in coastal polynyas, nucleating ice crystals adhere to rocks and sediments on the bottom, forming what is called 'anchor ice.' Although this has never been directly observed in polynyas because of the hazardous conditions, observations by Alaskan divers following severe autumnal storms have found sediment-laden frazil ice on the surface, and anchor ice on the bottom. Downwind of these polynya regions, there are also many observations of pack ice containing layers with large sediment concentrations. These observations suggest that as the amount of anchor ice increases, the buoyancy of the sediment/ice mixture lifts the material to the surface, where it accumulates downwind. At river deltas such as the Laptev River, this means that sediments carried by the river into the delta can be incorporated into the frazil ice, for later export across the Arctic. Laboratory studies also suggest that the Langmuir circulation may also directly mix bottom sediments into the water column, where these sediments are then incorporated into the frazil ice and carried to the surface. By a combination of these routes, the coastal polynyas probably serve as a source of the observed sediments in the polar ice. This mechanism also provides a route for sediments laden with contaminants or radionuclides carried into the polynya regions by the rivers, to be incorporated into the pack ice, and then be transported across the Arctic.

Biological Importance

In the winter Canadian Arctic, because the marine mammals living under the ice need breathing holes, these mammals tend to concentrate in the polynya regions. For example, the North Water contains large concentrations of white whales, narwhals, walruses, and seals, with polar bears foraging along the coast. Also, the major winter bird colonies in the Canadian islands are located adjacent to polynyas, especially the North Water, and archeological evidence shows that the coastal region adjacent to the NEW was the site of human settlements. All of this suggests that polynyas are vital for the overwinter survival of arctic species. In spring and summer, the polynya regions continue to have large concentrations of marine mammals. This is because, as the polynya regions become ice-free earlier than the rest of the pack, they annually absorb more solar radiation than an adjacent region covered with thick pack ice. As a result, the polynya regions in summer have a much greater primary productivity than regions with heavy winter pack ice, so that these regions are important feeding areas for whales. Also, in the US and Canadian Arctic, most of the whales migrate into the region through passages generated by the spring melt of polynyas. For example, the opening of the polynya region along the Alaskan Chukchi coast provides a whale migration route to the Beaufort Sea, and in the Canadian Arctic the early opening of the polynya regions provides migration routes for narwhals in Lancaster Strait.

Conclusions

Polynyas are persistent openings in the ice cover that in winter ventilate the warm ocean directly to the cold atmosphere. The major physical importance of the coastal polynyas is due to their large production of ice and brine, where the resultant dense water contributes to various Arctic, Antarctic, and North Pacific water masses. In the Southern Hemisphere, the winter convection within the mid-ocean polynyas also leads to cooling of the upwelled ocean water and its modification into Antarctic bottom water. Also, although this has not been elaborated on because of space considerations, the polynyas may enhance the exchange of gases such as carbon dioxide between the atmosphere and ocean. The biological importance of the polynyas is that at least in the US and Canadian Arctic, they serve as an important winter and summer habitat for marine birds and mammals. The polynyas also play a role in spring and summer as regions of early open water formation, and as sites of significant increases in primary productivity associated with the early absorption of incident solar radiation in the water column.

Acknowledgment

This material is based upon work supported by the National Science Foundation under Grant No. 9811097.

See also

Arctic Basin Circulation. Current Systems in the Southern Ocean. Langmuir Circulation and Instability. Marine Mammal Migrations and Movement Patterns. Marine Mammal Overview. Marine Mammals, History of Exploitation. Okhotsk Sea Circulation. Open Ocean Convection. Satellite Passive Microwave Measurements of Sea Ice. Satellite Remote Sensing SAR. Sea Ice: Overview; Variations in Extent and Thickness. Sub Ice-shelf Circulation and Processes. Surface, Gravity and Capillary Waves. Weddell Sea Circulation.

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POPULATION DYNAMICS MODELS

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doi:10.1006/rwos.2001.0409

Introduction

The general purpose of population models of plankton species is to describe and eventually to predict the changes in abundance, distribution, and production of targeted populations under forcing of the abiotic environment, food conditions, and predation. Computer-based approaches in plankton ecology were introduced during the 1970s with the application of population models to investigate large-scale population phenomena by the use of mathematical models.

Today, virtually every major scientific research project of population ecology has a modeling component. Population models are built for three main objectives: (1) to estimate the survival of individuals and the persistence of populations in their physical and biological environments, and to look at the factors and processes that regulate their variability; (2) to estimate the flow of energy and matter through a given population; and (3) to study different aspects of behavioral ecology. The study of internal properties of a population, like the various effects of individual variability, and the study of interactions between populations and successions of population are also topics related to population models. The field of biological modeling has diversified and, at present, complex mathematical approaches such as neural networks, genetic algorithms, and dynamical optimization are coming into use, along with the application of supercomputers. However, the use of models in marine research should always be accompanied by extensive field data and laboratory experiments, for initialization, verification or falsification, or continuous updating.

Approach for Modelling Plankton Populations

Population Structure and Units

A population is defined as a group of living organisms all of one species restricted to a given area and with limited exchanges of individuals from other populations. The first step in building a population model is to identify state variables (components of the population) and to describe the interactions between these state variables and external variables of the system and among the components themselves. The components of a population can be (1) the entire population (one component); (2) groups of individuals identified by a certain state: developmental stages, weight or size classes, age classes (fixed numbers of components); or (3) all individuals (varying numbers of components).