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SEA ICE

Overview

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Introduction

Sea ice, any form of ice found at sea that originated from the freezing of sea water, has historically been among the least-studied of all the phenomena that have a significant effect on the surface heat balance of the Earth. Fortunately, this neglect has recently lessened as the result of improvements in observational and operational capabilities in the polar ocean areas. As a result, considerable information is now available on the nature and behavior of sea ice as well as on its role in affecting the weather, the climate, and the oceanography of the polar regions and possibly of the planet as a whole.

Extent

Although the majority of Earth's population has never seen sea ice, in area it is extremely extensive: 7% of the surface of the Earth is covered by this material during some time of the year. In the northern hemisphere the area covered by sea ice varies between 8×10^6 and $15 \times 10^6\,km^2$, with the smaller number representing the area of multiyear (MY) ice remaining at the end of summer. In summer this corresponds roughly to the contiguous area of the United States and to twice that area in winter, or to between 5% and 10% of the surface of the northern hemisphere ocean. At maximum extent, the ice extends down the western side of the major ocean basins, following the pattern of cold currents and reaching the Gulf of St. Lawrence (Atlantic) and the Okhotsk Sea off the north coast of Japan (Pacific). The most southerly site in the northern hemisphere where an extensive sea ice cover forms is the Gulf of Bo Hai, located off the east coast of China at 40°N. At the end of the summer the perennial MY ice pack of the Arctic is primarily confined to the central Arctic Ocean with minor extensions into the Canadian Arctic Archipelago and along the east coast of Greenland.

In the southern hemisphere the sea ice area varies between 3×10^6 and $20 \times 10^6\,km^2$, covering between 1.5% and 10% of the ocean surface. The amount of MY ice in the Antarctic is appreciably less than in the Arctic, even though the total area affected by sea ice in the Antarctic is approximately a third larger than in the Arctic. These differences are largely caused by differences in the spatial distributions of land and ocean. The Arctic Ocean is effectively landlocked to the south, with only one major exit located between Greenland and Svalbard. The Southern Ocean, on the other hand, is essentially completely unbounded to the north, allowing unrestricted drift of the ice in that direction, resulting in the melting of nearly all of the previous season's growth.

Geophysical Importance

In addition to its considerable extent, there are good reasons to be concerned with the health and behavior of the world's sea ice covers. Sea ice serves as an insulative lid on the surface of the polar oceans. This suppresses the exchange of heat between the cold polar air above the ice and the relatively warm sea water below the ice. Not only is the ice itself a good insulator, but it provides a surface that supports a snow cover that is also an excellent insulator. In addition, when the sea ice forms with its attendant snow cover, it changes the surface albedo, α (i.e., the reflection coefficient for visible radiation) of the sea from that of open water ($\alpha = 0.15$) to that of newly formed snow ($\alpha = 0.85$), leading to a 70% decrease in the amount of incoming short-wave solar radiation that is absorbed. As a result, there are inherent positive feedbacks associated with the existence of a sea ice cover. For instance, a climatic warming will presumably reduce both the extent and the thickness of the sea ice. Both of these changes will, in turn, result in increases in the temperature of the atmosphere and of the sea, which will further reduce ice thickness and extent. It is this positive feedback that is a major factor in producing the unusually large increases in arctic temperatures that are forecast by numerical models simulating the effect of the accumulation of greenhouse gases.

The presence of an ice cover limits not only the flux of heat into the atmosphere but also the flux of moisture. This effect is revealed by the common presence of linear, local clouds associated with individual leads (cracks in the sea ice that are covered with either open water or thinner ice). In fact, sea ice exerts a significant influence on the radiative energy balance of the complete atmosphere–sea ice–ocean system. For instance, as the ice thickness increases in the range between 0 and 70 cm, there is an increase in the radiation absorption in the ice and a decrease in the ocean. There is also a decrease in the radiation adsorption by the total atmosphere–ice–ocean system. It is also known that the upper 10 cm of the ice can absorb over 50% of the total solar radiation, and that decreases in ice extent produce increases in atmospheric moisture or cloudiness, in turn altering the surface radiation budget and increasing the amount of precipitation. Furthermore, all the ultraviolet and infrared radiation is absorbed in the upper 50 cm of the ice; only visible radiation penetrates into the lower portions of thicker ice and into the upper ocean beneath the ice. Significant changes in the extent and/or thickness of sea ice would result in major changes in the climatology of the polar regions. For instance, recent computer simulations in which the ice extent in the southern hemisphere was held constant and the amount of open water (leads) within the pack was varied showed significant changes in storm frequencies, intensities and tracks, precipitation, cloudiness, and air temperature.

However, there are even less obvious but perhaps equally important air–ice and ice–ocean interactions. Sea ice drastically reduces wave-induced mixing in the upper ocean, thereby favoring the existence of a 25–50 m thick, low-salinity surface layer in the Arctic Ocean that forms as the result of desalination processes associated with ice formation and the influx of fresh water from the great rivers of northern Siberia. This stable, low-density surface layer prevents the heat contained in the comparatively warm (temperatures of up to $+3^{\circ}C$) but more saline denser water beneath the surface layer from affecting the ice cover. As sea ice rejects roughly two-thirds of the salt initially present in the sea water from which the ice forms, the freezing process is equivalent to distillation, producing both a low-salinity component (the ice layer itself) and a high-salinity component (the rejected brine). Both of these components play important geophysical roles. Over shallow shelf seas, the rejected brine, which is dense, cold, and rich in CO_2, sinks to the bottom, ultimately feeding the deep-water and the bottom-water layers of the world ocean. Such processes are particularly effective in regions where large polynyas exist (semipermanent open water and thin-ice areas at sites where climatically much thicker ice would be anticipated).

The 'fresh' sea ice layer also has an important geophysical role to play in that its exodus from the Arctic Basin via the East Greenland Drift Stream represents a fresh water transport of $2366\,km^3\,y^{-1}$ (*c.* 0.075 Sv). This is a discharge equivalent to roughly twice that of North America's four largest rivers combined (the Mississippi, St. Lawrence, Columbia, and Mackenzie) and in the world is second only to the Amazon. This fresh surface water layer is transported with little dispersion at least as far as the Denmark Strait and in all probability can be followed completely around the subpolar gyre of the North Atlantic. Even more interesting is the speculation that during the last few decades this fresh water flux has been sufficient to alter or even stop the convective regimes of the Greenland, Iceland and Norwegian Seas and perhaps also of the Labrador Sea. This is a sea ice-driven, small-scale analogue of the so-called halocline catastrophe that has been proposed for past deglaciations, when it has been argued that large fresh water runoff from melting glaciers severely limited convective regimes in portions of the world ocean. The difference is that, in the present instance, the increase in the fresh water flux that is required is not dramatic because at near-freezing temperatures the salinity of the sea water is appreciably more important than the water temperature in controlling its density. It has been proposed that this process has contributed to the low near-surface salinities and heavy winter ice conditions observed north of Iceland between 1965 and 1971, to the decrease in convection described for the Labrador Sea during 1968–1971, and perhaps to the so-called 'great salinity anomaly' that freshened much of the upper North Atlantic during the last 25 years of the twentieth century. In the Antarctic, comparable phenomena may be associated with freezing in the southern Weddell Sea and ice transport northward along the Antarctic Peninsula.

Sea ice also has important biological effects at both ends of the marine food chain. It provides a substrate for a special category of marine life, the ice biota, consisting primarily of diatoms. These form a significant portion of the total primary production and, in turn, support specialized grazers and species at higher trophic levels, including amphipods, copepods, worms, fish, and birds. At the upper end of the food chain, seals and walruses use ice extensively as a platform on which to haul out and give birth to young. Polar bears use the ice as a platform while hunting. Also important is the fact that in shelf seas such as the Bering and Chukchi, which are well mixed in the winter, the melting of the ice cover in the spring lowers the surface salinity, increasing the stability of the water column. The reduced mixing concentrates phytoplankton in the near-surface photic zone, thereby enhancing the overall intensity of the spring bloom. Finally, there are the direct effects of sea ice on human activities. The most important of these are its barrier action in limiting the use of otherwise highly advantageous ocean routes between the northern Pacific regions and Europe and its contribution to the numerous operational difficulties that must be overcome to achieve the safe extraction of the presumed oil and gas resources of the polar shelf seas.

Properties

Because ice is a thermal insulator, the thicker the ice, the slower it grows, other conditions being equal. As sea ice either ablates or stops growing during the summer, there is a maximum thickness of first-year (FY) ice that can form during a specific year. The exact value is, of course, dependent upon the local climate and oceanographic conditions, reaching values of slightly over 2 m in the Arctic and as much as almost 3 m at certain Antarctic sites. It is also clear that during the winter the heat flux from areas of open water into the polar atmosphere is significantly greater than the flux through even thin ice and is as much as 200 times greater than the flux through MY ice. This means that, even if open water and thin ice areas comprise less than 1–2% of the winter ice pack, lead areas must still be considered in order to obtain realistic estimates of ocean–atmosphere thermal interactions.

If an ice floe survives a summer, during the second winter the thickness of the additional ice that is added is less than the thickness of nearby FY ice for two reasons: it starts to freeze later and it grows slower. Nevertheless, by the end of the winter, the second-year ice will be thicker than the nearby FY ice. Assuming that the above process is repeated in subsequent years, an amount of ice is ablated away each summer (largely from the upper ice surface) and an amount is added each winter (largely on the lower ice surface). As the year pass, the ice melted on top each summer remains the same (assuming no change in the climate over the ice), while the ice forming on the bottom becomes less and less as a result of the increased insulating effect of the thickening overlying ice. Ultimately, a rough equilibrium is reached, with the thickness of the ice added in the winter becoming equal to the ice ablated in the summer. Such steady-state MY ice floes can be layer cakes of ten or more annual layers with total thicknesses in the range 3.5–4.5 m. Much of the uncertainty in estimating the equilibrium thickness of such floes is the result of uncertainties in the oceanic heat flux. However, in sheltered fiord sites in the Arctic where the oceanic heat flux is presumed to be near zero, MY fast ice with thicknesses up to roughly 15–20 m is known to occur. Another important factor affecting MY ice thickness is the formation of melt ponds on the upper ice surface during the summer in that the thicknesses and areal extent of these shallow-water bodies is important in controlling the total amount of short-wave radiation that is absorbed. For instance, a melt pond with a depth of only 5 cm can absorb nearly half the total energy absorbed by the whole system. The problem here is that good regional descriptive characterizations of these features are lacking as the result of the characteristic low clouds and fog that occur over the Arctic ice packs in the summer. Particularly lacking are field observations on melt pond depths as a function of environmental variables. Also needed are assessments of how much of the meltwater remains ponded on the surface of the ice as contrasted with draining into the underlying sea water. Thermodynamically these are very different situations.

Conditions in the Antarctic are, surprisingly, rather different. There, surface melt rates within the pack are small compared to the rates at the northern boundary of the pack. The stronger winds and lower humidities encountered over the pack also favor evaporation and minimize surface melting. The limited ablation that occurs appears to be controlled by heat transfer processes at the ice–water interface. As a result, the ice remains relatively cold throughout the summer. In any case, as most of the Antarctic pack is advected rapidly to the north, where it encounters warmer water at the Antarctic convergence and melts rapidly, only small amounts of MY ice remain at the end of summer.

Sea ice properties are very different from those of lake or river ice. The reason for the difference is that when sea water freezes, roughly one-third of the salt in the sea water is initially entrapped within the ice in the form of brine inclusions. As a result, initial ice salinities are typically in the range 10–12‰. At low temperatures (below $-8.7°C$), solid hydrated salts also form within the ice. The composition of the brine in sea ice is a unique function of the temperature, with the brine composition becoming more saline as the temperature decreases. Therefore, the brine volume (the volumetric amount of liquid brine in the ice) is determined by the ice temperature and the bulk ice salinity. Not only is the temperature of the ice different at different levels in the ice sheet but the salinity of the ice decreases further as the ice ages ultimately reaching a value of $\sim 3‰$ in MY ice. Brine volumes are usually lower in the colder upper portions of the ice and higher in the warmer, lower portions. They are particularly low in the above-sea-level part of MY ice as the result of the salt having drained almost completely from this ice. In fact, the upper layers of thick MY ice and of aged pressure ridges produce excellent drinking water when melted. As brine volume is the single most important parameter controlling the thermal, electrical, and mechanical properties of sea ice, these properties show associated large changes both vertically in the same ice sheet and between ice sheets of differing ages and histories. To add complexity to this situation, exactly how the brine is distributed within the sea ice also affects ice properties.

There are several different structural types of sea ice, each with characteristic crystal sizes and preferred crystal orientations and property variations. The two most common structural types are called congelation and frazil. In congelation ice, large elongated crystals extend completely through the ice sheet, producing a structure that is similar to that found in directionally solidified metals. In the Arctic, large areas of congelation ice show crystal orientations that are so similar as to cause the ice to have directionally dependent properties in the horizontal plane as if the ice were a giant single crystal. Frazil, on the other hand, is composed of small, randomly oriented equiaxed crystals that are not vertically elongated. Congelation is more common in the Arctic, while frazil is more common in the Antarctic, reflecting the more turbulent conditions characteristically found in the Southern Ocean.

Two of the more unusual sea ice types are both subsets of so-called 'underwater ice.' The first of these is referred to as platelet ice and is particularly common around margins of the Antarctic continent at locations where ice shelves exist. Such shelves not only comprise 30% of the coastline of Antarctica, they also can be up to 250 m thick. Platelet ice is composed of a loose open mesh of large platelets that are roughly triangular in shape with dimensions of 4–5 cm. In the few locations that have been studied, platelet ice does not start to develop until the fast ice has reached a thickness of several tens of centimeters. Then the platelets develop beneath the fast ice, forming a layer that can be several meters thick. The fast ice appears to serve as a superstrate that facilitates the initial nucleation of the platelets. Ultimately, as the fast ice thickens, it incorporates some of the upper platelets. In the McMurdo Sound region, platelets have been observed forming on fish traps at a depth of 70 m. At locations near the Filchner Ice Shelf, platelets have been found in trawls taken at 250 m. This ice type appears to be the result of crystal growth into water that has been supercooled a fraction of a degree. The mechanism appears to be as follows. There is evidence that melting is occurring on the bottom of some of the deeper portions of the Antarctic ice shelves. This results in a water layer at the ice–water interface that is not only less saline and therefore less dense than the underlying seawater, but also is exactly at its freezing point at that depth because it is in direct contact with the shelf ice. When this water starts to flow outward and upward along the base of the shelf, supercooling develops as a result of adiabatic decompression. This in turn drives the formation of the platelet ice.

The second unusual ice type is a special type of frazil that results from what has been termed suspension freezing. The conditions necessary for its formation include strong winds, intense turbulence in an open water area of a shallow sea and extreme sub-freezing temperatures. Such conditions are characteristically found either during the initial formation of an ice cover in the fall or in regions where polynya formation is occurring, typically by newly formed ice being blown off of a coast or a fast ice area leaving in its wake an area of open water. When such conditions occur, the water column can become supercooled, allowing large quantities of frazil crystals to form and be swept downward by turbulence throughout the whole water column. Studies of benthic microfossils included in sea ice during such events suggest that supercooling commonly reaches depths of 20–25 m and occasionally to as much as 50 m. The frazil ice crystals that form occur in the form of 1–3 mm diameter discoids that are extremely sticky. As a result, they are not only effective in scavenging particulate matter from the water column but they also adhere to material on the bottom, where they continue to grow fed by the supercooled water. Such so-called anchor ice appears to form selectively on coarser material. The resulting spongy ice masses that develop can be quite large and, when the turbulence subsides, are quite buoyant and capable of floating appreciable quantities of attached sediment to the surface. There it commonly becomes incorporated in the overlying sea ice. In rivers, rocks weighing as much as 30 kg have been observed to be incorporated into an ice cover by this mechanism. Recent interest in this subject has been the result of the possibility that this mechanism has been effective in incorporating hazardous material into sea ice sheets, which can then serve as a long-distance transport mechanism.

Drift and Deformation

If sea ice were motionless, ice thickness would be controlled completely by the thermal characteristics of the lower atmosphere and the upper ocean. Such ice sheets would presumably have thicknesses and physical properties that change slowly and continuously from region to region. However, even a casual examination of an area of pack ice reveals striking local lateral changes in ice thicknesses and characteristics. These changes are invariably caused by ice movements produced by the forces exerted on the ice by winds and currents. Such motions are rarely uniform and lead to the build-up of stresses within ice sheets. If these stresses become large enough, cracks may form and widen, resulting in the formation of leads. Such features can vary in width from a few meters to several kilometers and in length from a few hundred meters to several hundred kilometers. As mentioned earlier, during much of the year in the polar regions, once a lead forms it is immediately covered with a thin skim of ice that thickens with time. This is an ever-changing process associated with the movement of weather systems as one lead system becomes inactive and is replaced by another system oriented in a different direction. As lead formation occurs at varied intervals throughout the ice growth season, the end result is an ice cover composed of a variety of thicknesses of uniform sheet ice.

However, when real pack ice thickness distributions are examined (**Figure 1**), one finds that there is a significant amount of ice thicker than the 4.5–5.0 m maximum that might be expected for steady-state MY ice floes. This thicker ice forms by the closing of leads, a process that commonly results in the piling of broken ice fragments into long, irregular features referred to as pressure ridges. There are many small ridges and large ridges are rare. Nevertheless, the large ridges are very impressive, the largest free-floating sail height and keel depth reported to date in the Arctic being 13 and 47 m, respectively (values not from the same ridge). Particularly heavily deformed ice commonly occurs in a band of ~ 150 km running between the north coast of Greenland and the Canadian Arctic Islands and the south coast of the Beaufort Sea. The limited data available on Antarctic ridges suggest that they are generally smaller and less frequent than ridges in the Arctic Ocean. The general pattern of the ridging is also different in that the long sinuous ridges characteristic of the Arctic Ocean are not observed. Instead, the deformation can be better described as irregular hummocking accompanied by the extensive rafting of one floe over another. Floe sizes are also smaller as the result of the passage of large-amplitude swells through the ice. These swells, which are generated by the intense Southern Ocean storms that move to the north of the ice edge, result in the fracturing of the larger floes while the large vertical motions facilitate the rafting process.

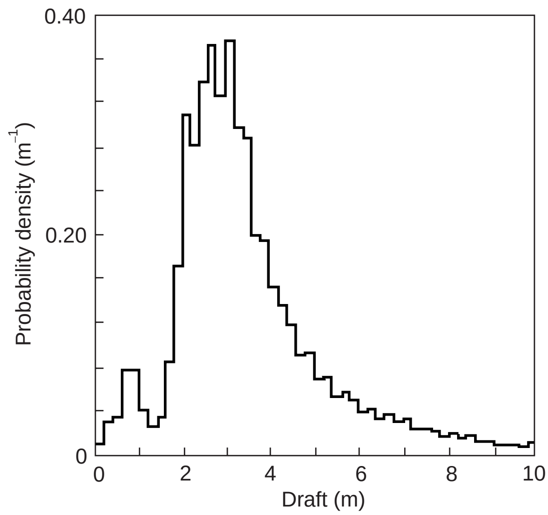

Figure 1 The distribution of sea ice drafts expressed as probability density as determined via the use of upward-looking sonar along a 1400 km track taken in April 1976 in the Beaufort Sea. All ice thicker than ~ 4 m is believed to be the result of deformation. The peak probabilities that occur in the range between 2.4 and 3.8 m represent the thicknesses of undeformed MY ice, while the values less than 1.2 m come from ice that ice that recently formed in newly formed leads.

Pressure ridges are of considerable importance for a variety of reasons. First, they change the surface roughness at the air–ice and water–ice interfaces, thereby altering the effective surface tractions exerted by winds and currents. Second, they act as plows, forming gouges in the sea floor up to 8 m deep when they ground and are pushed along by the ungrounded pack as it drifts over the shallower (< 60 m) regions of the polar continental shelves. Third, as the thickest sea ice masses, they are a major hazard that must be considered in the design of offshore structures. Finally, and most importantly, the ridging process provides a mechanical procedure for transferring the thinner ice in the leads directly and rapidly into the thickest ice categories.

Considerable information on the drift and deformation of sea ice has recently become available through the combined use of data buoy and satellite observations. This information shows that, on the average, there are commonly two primary ice motion features in the Arctic Basin. These are the Beaufort Gyre, a large clockwise circulation located in the Beaufort Sea, and the Trans-Polar Drift Stream, which transports ice formed on the Siberian Shelf over the Pole to Fram Strait between Greenland and Svalbard. The time required for the ice to complete one circuit of the gyre averages 5 years, while the transit time for the Drift Stream is roughly 3 years, with about 9% of the sea ice of the Arctic Basin (919 000 km^2) moving south through Fram Strait and out of the basin each year. There are many interesting features of the ice drift that exist over shorter time intervals. For instance, recent observations show that the Beaufort Gyre may run backward (counterclockwise) over appreciable periods of time, particularly in the summer and fall. There have even been suggestions that such reversals can occur on decadal timescales. Typical pack ice velocities range from 0 to 20 $cm\,s^{-1}$, although extreme velocities of up to 220 $cm\,s^{-1}$ (4.3 knots) have been recorded during storms. During winter, periods of zero ice motion are not rare. During summers, when considerable open water is present in the pack, the ice appears to be in continuous motion. The highest drift velocities are invariably observed near the edge of the pack. Not only are such locations commonly windy, but the floes are able to move toward the free edge with minimal inter-floe interference. Ice drift near the Antarctic continent is generally westerly, becoming easterly further to the north, but in all cases showing a consistent northerly diverging drift toward the free ice edge.

Trends

Considering the anticipated geophysical consequences of changes in the extent of sea ice, it is not surprising that there is considerable scientific interest in the subject. Is sea ice expanding and thickening, heralding a new glacial age, or retreating and thinning before the onslaught of a greenhouse-gas-induced heatwave? One thing that should be clear from the preceding discussion is that the ice is surprisingly thin and variable. Small changes in meteorological and oceanographic forcing should result in significant changes in the extent and state of the ice cover. They could also produce feedbacks that might have significant and complex climatic consequences.

Before we examine what is known about sea ice variations, let us first examine other related observations that have a direct bearing on the question of sea ice trends. Land station records for 1966–1996 show that the air temperatures have increased, with the largest increases occurring winter and spring over both north-west North America and Eurasia, a conclusion that is supported by increasing permafrost temperatures. In addition, meteorological observations collected on Russian NP drifting stations deployed in the Arctic Basin show significant warming trends for the spring and summer periods. It has also recently been suggested that when proxy temperature sources are considered, they indicate that the late twentieth-century Arctic temperatures were the highest in the past 400 years.

Recent oceanographic observations also relate to the above questions. In the late 1980s the balance between the Atlantic water entering the Arctic Basin and the Pacific water appears to have changed, resulting in an increase in the areal extent of the more saline, warmer Atlantic water. In addition, the Atlantic water is shallower than in the past, resulting in temperature increases of as much as 2°C and salinity increases of up to 2.5‰ at depths of 200 m. The halocline, which isolates the cold near-surface layer and the overlying sea ice cover from the underlying warmer water, also appears to be thinning, a fact that could profoundly affect the state of the sea ice cover and the surface energy budget in the Arctic. Changes revealed by the motions of data buoys placed on the ice show that there has been a weakening of the Beaufort Sea Gyre and an associated increased divergence of the ice peak. There are also indications that the MY ice in the center of the Beaufort Gyre is less prevalent and thinner than in the past and that the amount of surface melt increased from ~ 0.8 m in the mid-1970s to ~ 2 m in 1997. This conclusion is supported by the operational difficulties encountered by recent field programs such as SHEBA that attempted to maintain on-ice measurements. The increased melt is also in agreement with observed decreases in the salinity of the near-surface water layer.

It is currently believed that these changes appear to be related to atmospheric changes in the Polar Basin where the mean atmospheric surface pressure is decreasing and has been below the 1979–95 mean every year since 1988. Before about 1988–99 the Beaufort High was usually centered over 180° longitude. After this time the high was both weaker and typically confined to more western longitudes, a fact that may account for lighter ice conditions in the western Arctic. There also has been a recent pronounced increase in the frequency of cyclonic storms in the Arctic Basin.

So are there also direct measurements indicating decreases in ice extent and thickness? Historical data based on direct observations of sea ice extent are rare, although significant long-term records do exist for a few regions such as Iceland where sea ice has an important effect on both fishing and transportation. In monitoring the health of the world's sea ice covers the use of satellite remote sensing is essential because of the vast remote areas that must be surveyed. Unfortunately, the satellite record is very short. If data from only microwave remote sensing systems are considered, because of their all-weather capabilities, the record is even shorter, starting in 1973. As there was a 2-year data gap between 1976 and 1978, only 25 years of data are available to date. The imagery shows that there are definitely large seasonal, interannual and regional variations in ice extent. For instance, a decrease in ice extent in the Kara and Barents Seas contrasts with an increase in the Baffin Bay/Davis Strait region and out-of-phase fluctuations occur between the Bering and the Okhotsk Seas. The most recent study, which examined passive microwave data up to December 1996, concludes that the areal extent of Arctic sea ice has decreased by 2.9% $\pm$ 0.4% per decade. In addition, record or near-record minimum areas of Arctic sea ice have been observed in 1990, 1991, 1993, 1995, and 1997. A particularly extreme recession of the ice along the Beauford coast was also noted in the fall of 1998. Russian ice reconnaissance maps also show that a significant reduction in ice extent and concentration has occurred over much of the Russian Arctic Shelf since 1987.

Has a systematic variation also been observed in ice thickness? Unfortunately there is, at present, no satellite-borne remote sensing technique that can measure sea ice thicknesses effectively from above. There is also little optimism about the possibilities of developing such techniques because the extremely lossy nature of sea ice limits penetration of electromagnetic signals. Current ice thickness information comes from two very different techniques: *in situ* drilling and upward-looking, submarine-mounted sonar. Although drilling is an impractical technique for regional studies, upward-looking sonar is an extremely effective procedure. The submarine passes under the ice at a known depth and the sonar determines the distance to the underside of the ice by measuring the travel times of the sound waves. The result is an accurate, well-resolved under-ice profile from which ice draft distributions can be determined and ice thickness distributions can be estimated based on the assumption of isostacy. Although there have been a large number of under-ice cruises starting with the USS *Nautilus* in 1958, to date only a few studies have been published that examine temporal variations in ice thickness in the Arctic. The first compared the results of two nearly identical cruises: that of the USS *Nautilus* in 1958 with that of the USS *Queenfish* in 1970. Decreases in mean ice thickness were observed in the Canadian Basin (3.08–2.39 m) and in the Eurasian Basin (4.06–3.57 m). The second study has compared the results of two Royal Navy cruises made in 1976 and 1987, and obtained a 15% decrease in mean ice thickness for a 300 000 km^2 area north of Greenland. Although these studies showed similar trends, the fact that they each only utilized two years' data caused many scientists to feel that a conclusive trend had not been established. However, a recent study has been able to examine this problem in more detail by comparing data from three submarine cruises made in the 1990s (1993, 1996, 1997) with the results of similar cruises made between 1958 and 1976. The area examined was the deep Arctic Basin and the comparisons used only data from the late summer and fall periods. It was found that the mean ice draft decreased by about 1.3 m from 3.1 m in 1958–76 to 1.8 m in the 1990s, with a larger decrease occurring in the central and eastern Arctic than in the Beaufort and Chukchi Seas. This is a very large difference, indicating that the volume of ice in the region surveyed is down by some 40%. Furthermore, an examination of the data from the 1990s suggests that the decrease in thickness is continuing at a rate of about 0.1 m y^{-1}.

Off the Antarctic the situation is not as clear. One study has suggested a major retreat in maximum sea ice extent over the last century based on comparisons of current satellite data with the earlier positions of whaling ships reportedly operating along the ice edge. As it is very difficult to access exactly where the ice edge is located on the basis of only ship-board observations, this claim has met with some skepticism. An examination of the satellite observations indicates a very slight increase in areal extent since 1973. As there are no upward-looking sonar data for the Antarctic Seas, the thickness database there is far smaller than in the Arctic. However, limited drilling and airborne laser profiles of the upper surface of the ice indicate that in many areas the undeformed ice is very thin (60–80 cm) and that the amount of deformed ice is not only significantly less than in the Arctic but adds roughly only 10 cm to the mean ice thickness (**Figure 2**).

What is one to make of all of this? It is obvious that, at least in the Arctic, a change appears to be under way that extends from the top of the atmosphere to depths below 100 m in the ocean. In the middle of this is the sea ice cover, which, as has been shown, is extremely sensitive to environmental

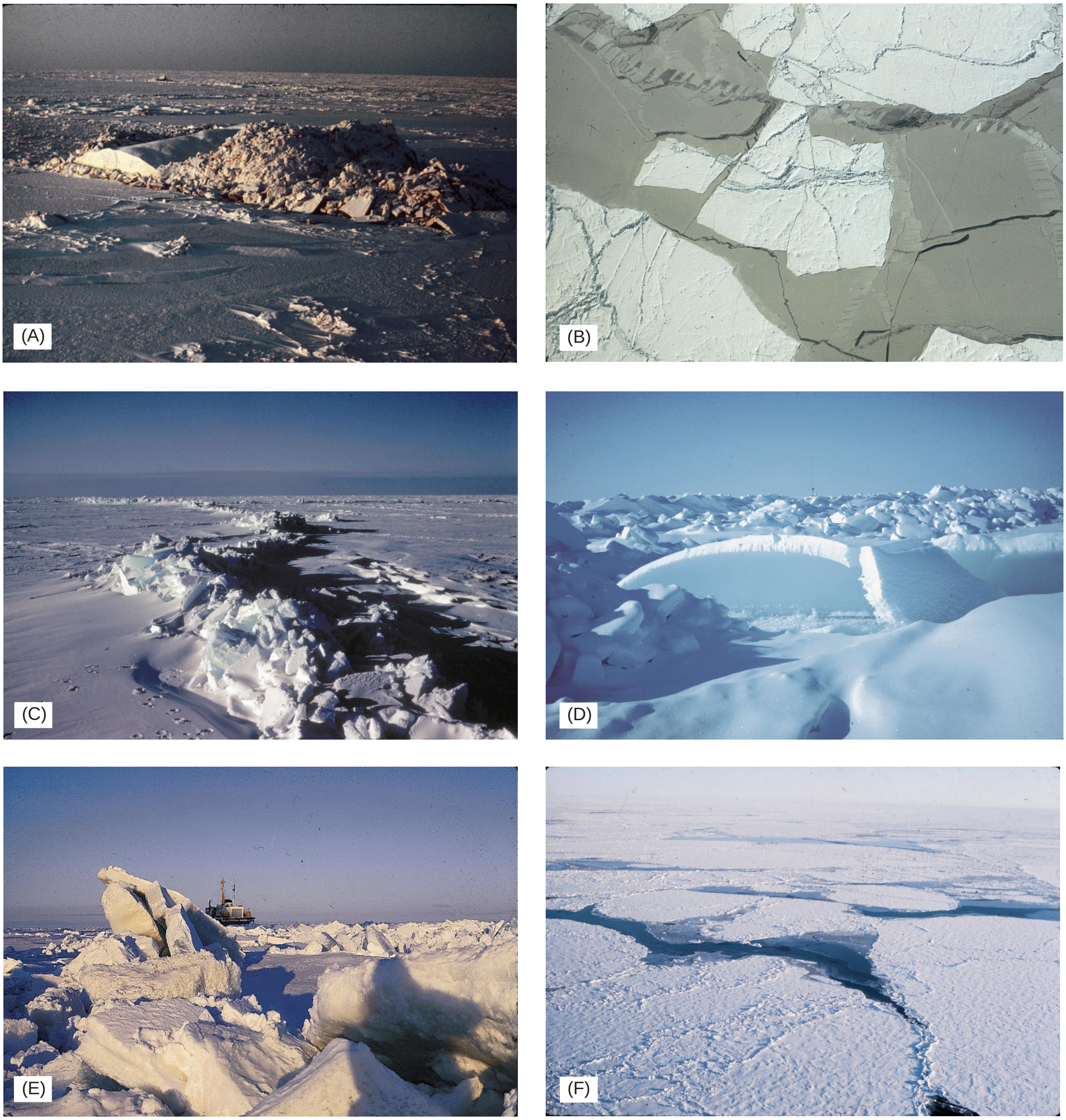

Figure 2 (A) Ice gouging along the coast of the Beaufort Sea. (B) Aerial photograph of an area of pack ice in the Arctic Ocean showing a recently refrozen large lead that has developed in the first year. The thinner newly formed ice is probably less than 10 cm thick. (C) A representative pressure ridge in the Arctic Ocean. (D) A rubble field of highly deformed first-year sea ice developed along the Alaskan coast of the Beaufort Sea. The tower in the far distance is located at a small research station on one of the numerous off-shore islands located along this coast. (E) Deformed sea ice along the NW Passage, Canada. (F) Aerial photograph of pack ice in the Arctic Ocean.

changes. What is not known is whether these changes are part of some cycle or represent a climatic regime change in which the positive feedbacks associated with the presence of a sea ice cover play an important role. Also not understood are the interconnections between what is happening in the Arctic and other changes both inside and outside the Arctic. For instance, could changes in the Arctic system drive significant lower-latitude atmospheric and oceanographic changes or are the Arctic changes driven by more dynamic lower-latitude processes? In the Antarctic the picture is even less clear, although changes are known to be underway, as evidenced by the recent breakup of ice shelves along the eastern coast of the Antarctic Peninsula. Not surprisingly, the scientific community is currently devoting considerable energy to attempting to answer these questions. One could say that a cold subject is heating up.

See also

Antarctic Circumpolar Current. Arctic Basin Circulation. Icebergs. Sea Ice: Variations in Extent and Thickness.

Further Reading

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Variations in Extent and Thickness

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This review considers the seasonal and interannual variability of sea ice extent and thickness in the Arctic and Antarctic, and the downward trends which have recently been shown to exist in Arctic thickness and extent. There is no evidence at present for any thinning or retreat of the Antarctic sea ice cover.

Sea Ice Extent

Arctic

Seasonal variability The best way of surveying sea ice extent and its variability is by the use of satellite imagery, and the most useful imagery on the large scale is passive microwave, which identifies types of surface through their natural microwave emissions, a function of surface temperature and emissivity. **Figure 1** shows ice extent and concentration maps for the Arctic for each month, averaged over the period 1979–87, derived from the multifrequency SMMR (scanning multichannel microwave radiometer) sensor aboard the Nimbus-7 satellite. This instrument gives ice concentration and, through comparison of emissions at different frequencies, the percentage of the ice cover that is multiyear ice, i.e. ice which has survived at least one summer of melt. The ice concentrations are estimated to be accurate to $\pm 7\%$.

At the time of maximum advance, in February and March (**Figure 1A**), an ice cover fills the entire Arctic Ocean. The Siberian shelf seas are also ice-covered to the coast, although the warm inflow from the Norwegian Atlantic Current keeps the western part of the Barents Sea open. There is also a bight of open water to the west of Svalbard, kept open by the warm West Spitsbergen Current and formerly known as Whalers' Bay because it allowed sailing whalers to reach high latitudes. It is here that open sea is found closest to the Pole in winter – beyond 81° in some years. The east coast of Greenland has a sea ice cover along its entire length (although in mild winters the ice fails to reach Cape Farewell); this is transported out of Fram Strait by the Trans Polar Drift Stream and advected southward in the East Greenland Current, the strongest part of the current (and so the fastest ice drift) being concentrated at the shelf break. The Odden ice tongue at 72–75°N can be seen in these averaged maps as a distinct bulge in the ice edge, visible from January until April with an ice concentration of 20–50%. During any given year the Odden feature usually develops in the shape of a tongue, covering the region influenced by the Jan Mayen Current (a cold eastward offshoot of the East Greenland Current) and composed mainly of locally formed pancake ice.

Moving round Cape Farewell there is a thin band of ice off West Greenland (called the 'Storis'), the