Polynyas in the Southern Ocean

They are vast gaps in the sea ice around Antarctica. By exposing enormous areas of seawater to the frigid air, they help to drive the global heat engine that couples the ocean and the atmosphere

by Arnold L. Gordon and Josefino C. Comiso

During the austral winter (the months between June and September) as much as 20 million square kilometers of ocean surrounding Antarctica—an area about twice the size of the continental U.S.—is covered by ice. For more than two centuries, beginning with the voyages of Captain James Cook in the late 18th century, explorers, whalers and scientists charted the outer fringes of the ice pack from on board ship. Nevertheless, except for reports from the few ships that survived after being trapped in the pack ice, not much was known about the ice cover itself.

Since 1973, however, satellites bearing passive microwave sensors have made it possible to survey the ice cover routinely from space, and these observations have brought about a marked change in investigators' view of the Antarctic ice. One of the most surprising findings of the satellite era is that the ice cover is not at all a continuous blanket. Within its borders there are many small breaks, on the scale of from one to 10 kilometers, called leads. More surprisingly, there are sometimes vast regions—up to 350,000 square kilometers in area—that are completely free of ice.

ARNOLD L. GORDON and JOSEFINO C. COMISO combine sea- and satellite-based research in their study of polynyas. Gordon is professor of physical oceanography at Columbia University and is on the senior staff of Columbia's Lamont-Doherty Geological Observatory. His research is focused on large-scale circulation and mixing in the ocean and their relation to the global climate. Comiso is a physical scientist at the National Aeronautics and Space Administration's Goddard Space Flight Center. He went to Goddard in 1979 after doing research in experimental particle physics at various institutions. At Goddard he has helped to demonstrate the utility of passive-microwave and infrared data from satellites in the study of oceanic and atmospheric processes.

In these regions, called polynyas, the surface waters of the Southern Ocean (the ocean surrounding Antarctica) are bared to the frigid polar atmosphere. Polynyas and their effects are only incompletely understood, but it now appears they are both a result of the dramatic interaction of ocean and atmosphere that takes place in the Antarctic and a major participant in it. The exchanges of energy, water and gases between the ocean and the atmosphere around Antarctica have a major role in determining the large-scale motion, temperature and chemical composition of the ocean and atmosphere throughout the globe. Polynyas accelerate these processes by exposing the surface of the Southern Ocean directly to the atmosphere.

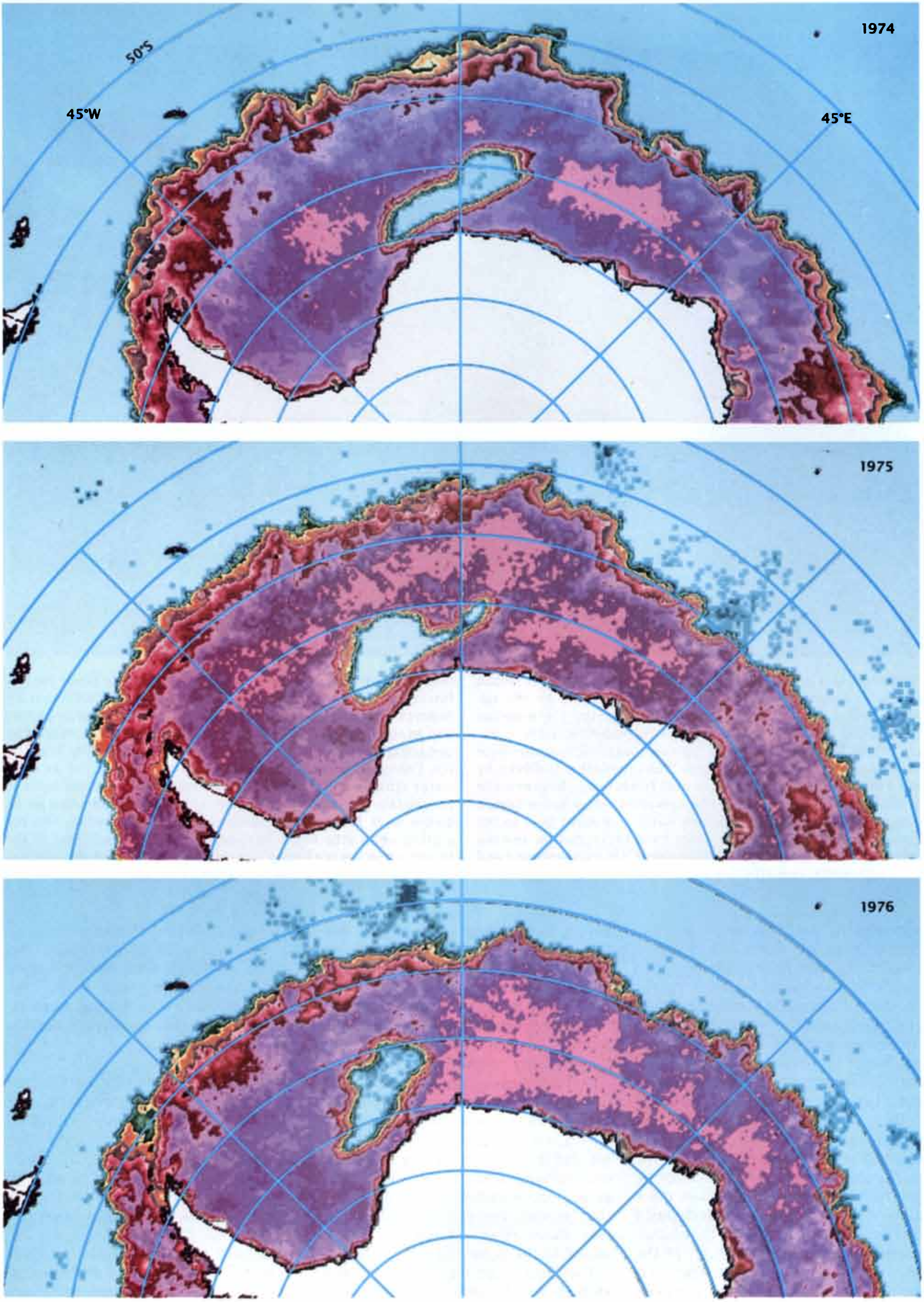
There are two general kinds of polynyas: coastal polynyas and open-ocean polynyas. Coastal polynyas develop when strong local winds originating on the Antarctic continent blow ice away from the shoreline as it freezes, leaving an ice-free area between the coast and the ice pack. Even before satellite data were available, investigators had known about the existence of coastal polynyas. They were very surprised, however, to learn from satellite observations how widespread coastal polynyas are and how large they can become. (In some coastal polynyas the distance from the shoreline to the border of the ice pack is as much as 50 to 100 kilometers.)

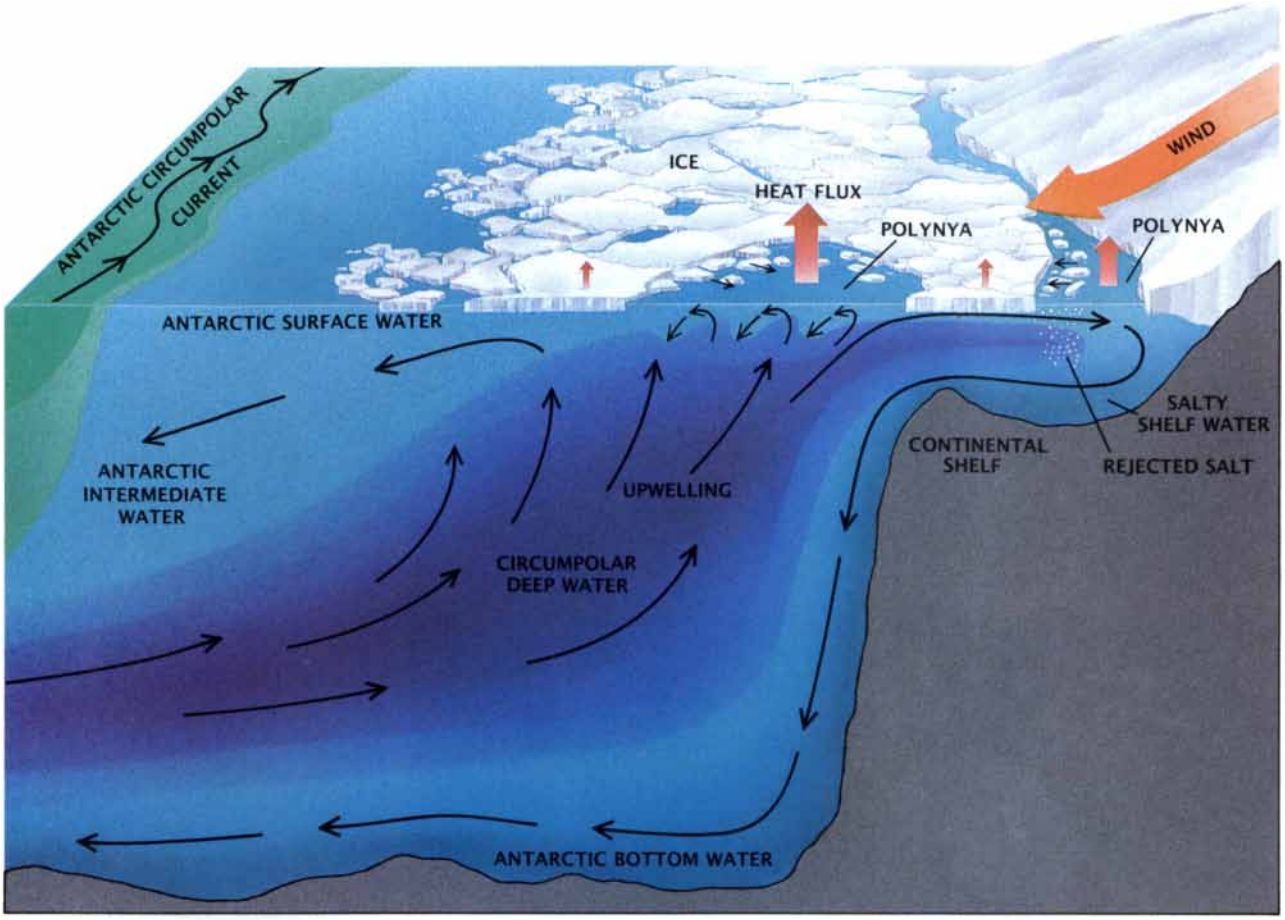
Open-ocean polynyas form within the body of the ice cover, far from the coast. Some of these are by far the largest and longest-lived polynyas. It is not yet fully understood what forces create and sustain open-ocean polynyas, but ship and satellite data gathered by us and by other investigators are enabling oceanographers to devise reasonable hypotheses.

In order to understand the specific forces that create and sustain polynyas and the effects polynyas can have, one must first understand the role the Southern Ocean plays in the general circulation of the world ocean and in the global climate as a whole. Because the Southern Ocean has extensive open connections to the rest of the world ocean, and because it is much larger than the polar ocean in the Arctic region, the Antarctic plays a larger role in the global ocean circulation than the Arctic does.

When solar radiation warms the tropical and subtropical oceans, the resulting heat diffuses downward into deeper water. Heat from the sun also causes relatively high rates of evaporation, which raises the salinity of the surface waters; the excess salt, like the heat, diffuses into the depths. The warmth and salinity of the deep water are also enhanced by deep-reaching mixing events in the North Atlantic, in which relatively warm, high-salinity surface water is mixed downward. The resulting mass of warm, salty deep water gradually spreads toward the Southern Ocean. In the Antarctic this water, now called the Circumpolar Deep Water, rises toward the surface. There it gives up some heat to the

WEDDELL POLYNYA, an enormous ice-free region amid the ice cover near the Weddell Sea, formed during three consecutive Southern Hemisphere winters. In these satellite images, which were made in September of 1974 (*top*), 1975 (*middle*) and 1976 (*bottom*), the white region represents the Antarctic landmass and colored regions represent ocean areas covered by various concentrations of sea ice. Pink and purple regions are almost completely covered by ice and light blue regions are ice-free. In summer the polynya disappeared with the melting of the ice cover. At its largest the polynya measured about 350 by 1,000 kilometers. It had measurable effects on the temperature of the underlying ocean at depths as great as 2,500 meters.


1974
50°S
45°W
45°E
1975
1976



MERIDIONAL CIRCULATION PATTERN of the Southern Ocean (the ocean surrounding Antarctica) is dominated by the upwelling of a warm, salty water mass called the Circumpolar Deep Water and its transformation into Antarctic Surface Water, which ultimately sinks to become Antarctic Intermediate Water and Antarctic Bottom Water. The circulation is driven by wind and the exchange of heat and fresh water between the ocean and the atmosphere. The upwelled water is converted into cold, relatively fresh surface water as it loses heat to the atmosphere and gains fresh water from precipitation and the melting of ice. Some of the surface water moves northward and gradually sinks, contributing to the formation of Antarctic Intermediate Water. Another fraction of the surface water moves toward the pole; it eventually sinks and flows northward as Antarctic Bottom Water. The circulation is influenced by polynyas. In so-called open-ocean polynyas (*center*) heat is vented to the atmosphere rapidly because there is no insulating layer of ice. Convection currents, in which warm water rises as cold water sinks, accelerate the movement of warm water toward the surface. So-called coastal polynyas (*right*) form when ice is blown away from the continent as fast as it freezes. The resulting open area vents heat rapidly, and the salt that is rejected when sea ice forms increases the density of the surface water and accelerates the formation of Antarctic Bottom Water.

atmosphere and becomes a cold, dense mass of water, which sinks toward the sea floor. This so-called Antarctic Bottom Water then moves northward along the ocean floor, traveling well beyond the Equator; it is the major mass of bottom water in the world. As it moves north it gradually mixes upward, and the cycle of warming and cooling begins again.

The Southern Ocean is thus one part of an enormous heat engine that drives the motions of much of the world ocean. In addition, the massive overturning of water that takes place in the Antarctic provides a mechanism by which the chemistry of the atmosphere can affect the chemistry of the deep ocean and vice versa. The overturning in a sense ventilates the deep ocean, by drawing water to the surface, allowing it to approach equilibrium with the temperature and composition of the atmosphere and forcing it downward again. The process cools the deep ocean, lowers its salinity and restores oxygen levels that have been depleted by organisms. The deep-ocean overturning may also be significant in establishing a rough balance between the oceanic concentrations of such dissolved gases as carbon dioxide and the levels of those gases in the atmosphere. Hence the overturning is an important factor in such events as the "greenhouse warming" that may take place as carbon dioxide gas is added to the atmosphere.

The heat engine's effects do not stop there. The overall rate at which heat is transferred from the Equator to the pole helps to determine the degree to which temperature varies with latitude on a global scale. This in turn has a part in driving many of the processes that govern the earth's weather and climate.

Perhaps the most important forces driving overturning in the Southern Ocean are buoyancy and the wind. Buoyancy gives the ocean a layered structure, in which masses of water are stratified according to their density (which in turn is determined by the water's temperature and salinity). The wind, on the other hand, tends to disturb this stratification. In addition, the exchange of heat and fresh water between the surface water and the atmosphere alters the density of the surface water, and so it can stimulate convection currents (in which buoyant water moves upward and denser water moves downward) that lead to a rearrangement of the stratification.

The top layer of water in the Southern Ocean, extending to a depth of about 100 meters, is called the Antarctic Surface Water. The Antarctic Surface Water is cold because of its proximity to the extremely cold Antarctic atmosphere, and it is relatively fresh because in the Southern Ocean precipitation (and the melting of Antarctic glacial ice) exceeds evaporation.

North of about 65 degrees south latitude, prevailing winds push much of the surface water farther to the north—away from the pole—while south of that latitude other winds push surface water to the south, toward the pole. The resulting divergence at 65 degrees south causes an upwelling: deeper water is lifted to replace the water that has been pushed north or south. The effect is to bring the warmer, saltier layer below the Antarctic Surface Water up toward the surface, where it is converted into Antarctic Surface Water.

The source of the warmer water is the Circumpolar Deep Water, which is drawn to the Southern Ocean in part by the wind-driven upwelling. Although the Circumpolar Deep Water, which extends to a depth of roughly 2,000 meters, is warmer than the surface water, it is still slightly denser because it has relatively high salinity. For that reason it tends to remain below the surface water.

Nevertheless, the surface water and the deep water south of about 60 degrees south latitude are so similar in density that their stratification pattern is only marginally stable. Very small forces can disturb it. Those forces are provided by the wind and by changes in the freshwater balance of the surface layer. Strong winds can greatly enhance the mixing of the two layers, particularly if ice floes are present to help create turbulence. The formation of sea ice in the winter also has a role in this mixing: when seawater freezes, the ice crystals reject much of the seawater's salt, expelling it in a concentrated brine that increases the salinity of the surface layer and thereby makes it more susceptible to mixing with the underlying deep water.

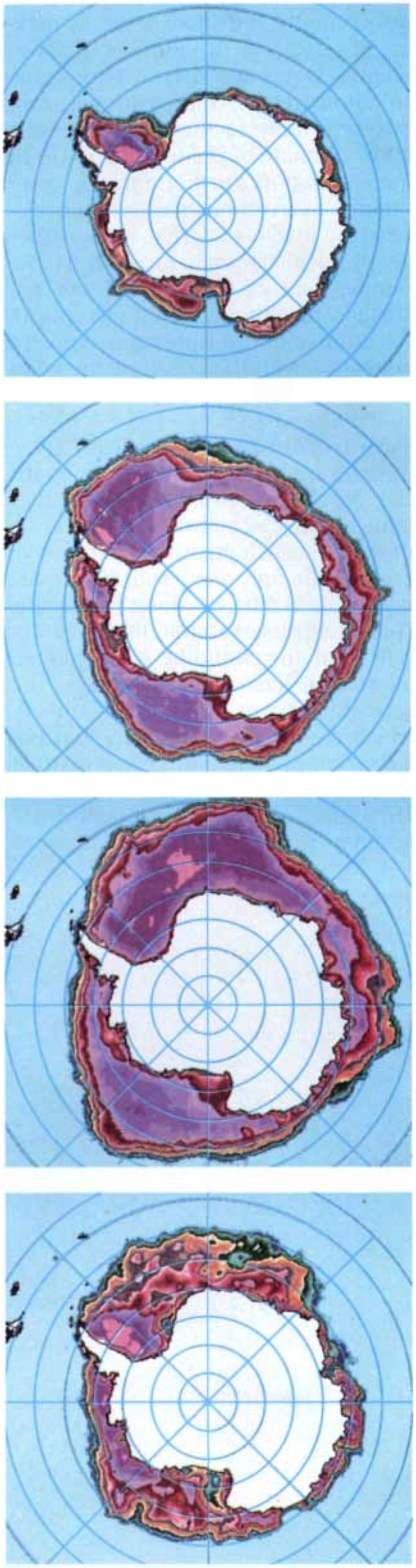
When the Circumpolar Deep Water mixes upward as a result of these processes, it vents heat to the atmosphere and cools, becoming denser. At the same time much of the surface water continues to be pushed either toward or away from the pole by the prevailing winds. The poleward-flowing portion continues to increase in density as it mixes with the brine rejected by newly forming sea ice. When this surface water reaches the Antarctic continental shelf, it sinks, flowing off the continental shelf to the ocean bottom, where it forms the Antarctic Bottom Water. In this way the effects of buoyancy and wind have combined to draw warm deep water from northern latitudes, transfer its heat to the Antarctic atmosphere and send it sinking toward the ocean floor.

Although the formation of the ice cover acts to accelerate this heat engine, the presence of the ice itself paradoxically tends to impede the deep-ocean overturning. The ice cover insulates the ocean surface, inhibiting the venting of oceanic heat. Some heat is still conducted to the atmosphere through the ice, but conduction is not nearly as efficient as the direct exposure of open water to the atmosphere would be; a layer of ice one meter thick (somewhat thicker than most of the Antarctic ice cover) can reduce the heat loss of the winter ocean by a factor of as much as 10 to 100.

How do polynyas, in which the ice cover is breached, affect these processes? This question would be impossible to address without data from satellites. Satellite observations provide consistent, repetitive and long-term coverage, and they also make it possible for investigators to follow changes that take place over time frames as short as a week or even a single day.

Satellite-borne sensors can operate in a variety of wavelengths and observing modes. The sensor that has shown itself to be the most versatile and useful for observations in polar regions is the passive microwave radiometer, which detects the radiation having wavelengths between one millimeter and one meter that is emitted naturally by various materials. This radiation is emitted during dark periods as well as during daylight hours and passes through most cloud cover, making it possible to observe a given region at any time of day and through almost any kind of weather. The microwave radiometer is ideal for monitoring sea-ice cover, because at some microwave wavelengths the emissivity of ice and water is very different.

The amount of radiation emitted in a given wavelength by an area of sea ice depends on a number of variables, including the ice's temperature, thick-



EXTENT of the Antarctic ice cover varies from season to season. These satellite images were made in (*from top to bottom*) March, June, September and December of 1984—respectively the southern summer, fall, winter and spring. In the southern summer ice covers about four million square kilometers of ocean, and in the winter it covers about 20 million.

ness, salinity and snow cover. By making observations in a number of wavelengths simultaneously, it is possible to eliminate the complications introduced by these factors and to derive a good estimate of the total ice cover in a given region. Furthermore, by combining observations in different wavelengths, one can derive many other geophysical parameters, such as the temperature of the ice and the sea surface, the amount of water vapor in the atmosphere, the position of the ice edge and even the speed of the wind over the ocean.

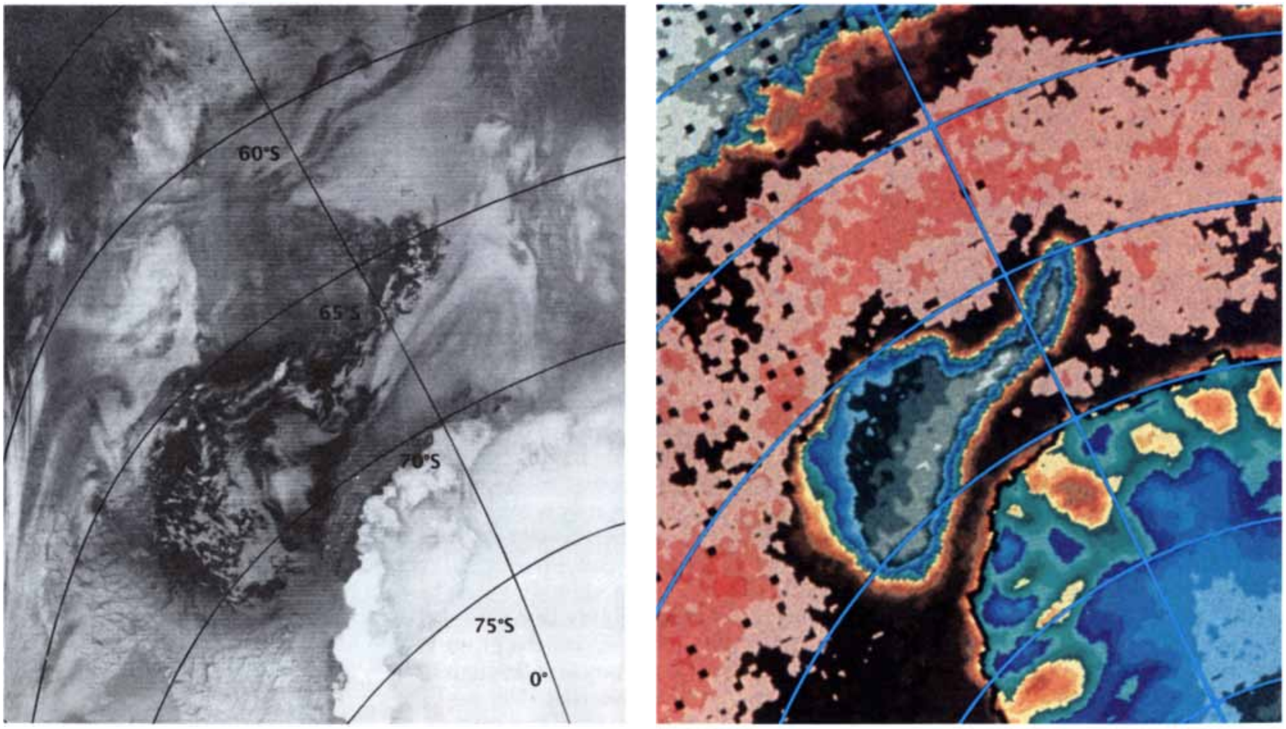
The first spaceborne passive microwave sensor was the Electrically Scanning Microwave Radiometer on board the *Nimbus 5* satellite, which was launched in December, 1972. This radiometer, which measured microwave radiation in only one frequency, transmitted good data for about four years. For later observations investigators relied on the Scanning Multichannel Microwave Radiometer on board the satellite *Nimbus 7*. This instrument, which recorded the intensity and polarization of radiation in five distinct frequencies, was in operation from 1978 until 1987, when the microwave scanner was turned off because of irregularities in the satellite's orientation. In 1987 a new sensor, called the Special Sensor Microwave Imager, was launched as part of the Defense Meteorological Satellite Program, ensuring continuous satellite coverage.

The existence and extent of polynyas are among the most interesting findings to come from satellite observation of the Antarctic. As we have mentioned, there are two kinds of polynyas: coastal polynyas and open-ocean polynyas. Satellite data, shipboard observations and theoretical analysis have now shown that the two kinds of polynyas are the result of very different causes and have quite different effects on the deep-ocean overturning.

The coastal polynyas are essentially sea-ice factories. They appear when local winds push newly forming sea ice away from the continent as quickly as it freezes. This exposes an area of open ocean on which more ice can form, continuing the process. Coastal polynyas are also called latent-heat polynyas, because the heat they release to the atmosphere is primarily in the form of the "latent heat" that liquid water gives off while it hovers at a steady temperature in the process of freezing. The heat flux to the atmosphere due to latent-heat polynyas is thought to be in excess of 300 watts per square meter, enough to add a 10-centimeter-thick layer of new ice (which is subsequently removed by the wind) to the coastal region every day. The ice generated in latent-heat polynyas may supply much of the sea ice in the adjacent ocean.

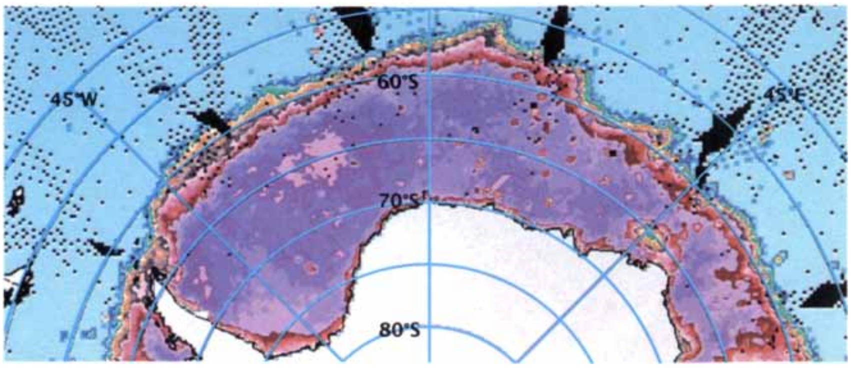
Meanwhile, as the ice forms within the polynya, the brine it rejects raises the salinity of the water overlying the continental shelf and helps to drive the formation of the Antarctic Bottom Water. According to rough calculations based on satellite data, the formation of ice in coastal polynyas leaves behind enough salt to form bottom water from Antarctic Surface Water at the rate of about 10 million cubic meters per second.

The enormous scale at which coastal polynyas create ice, cool the ocean and add salt to the Antarctic Bottom Water took oceanographers completely by surprise when it was first deduced from satellite observations. The knowledge we have gained about coastal polynyas has helped to explain several previously puzzling features



SATELLITE IMAGES of the Weddell Polynya made in August, 1975, illustrate the advantages of passive-microwave imagery (*right*) over conventional infrared imagery (*left*). In the infrared image the polynya is visible as the dark area at the center, but cloud cover makes it impossible to determine the polynya's extent. In the passive-microwave image it is possible not only to determine the precise shape of the polynya but also to identify such important features as the border between the Antarctic ice cover and the open ocean (*boundary between blue and gray at top left*) and the edge of the continental landmass (*orange border at bottom right*). In this image the various colors represent the "brightness" of the microwave radiation emitted by materials on the earth's surface. White and gray indicate the faintest emission, which signifies areas of open water

of the Antarctic ocean, such as the high salinity of the waters overlying the continental shelf (which had been measured during the austral summers) and the large quantities of Antarctic Bottom Water that flow from the Antarctic into the world ocean.



COSMONAUT POLYNYA, in the Cosmonaut Sea at 45 degrees east longitude and 65 degrees south latitude, marks a region where polynyas often appear. The fact that certain geographic locations are the sites of frequent polynyas and areas of poor ice cover lends support to the theory that the topography of the ocean bottom can influence the formation of polynyas. This image was made in September, 1986.

The forces that create and sustain open-ocean polynyas are somewhat more complex than those underlying coastal polynyas. Open-ocean polynyas probably form because of convection cells: vertical circulation patterns in which, over an area a few kilometers across, warm water (in this case water from the Circumpolar Deep Water) rises to the surface, cools and then sinks, to be replaced by more rising warm water. In open-ocean polynyas the continuously rising warm water would melt any ice on the surface and prevent further ice from forming. Open-ocean polynyas are also called sensible-heat polynyas, because the process in which they give up heat is directly associated with a change in temperature—it can be sensed.

Because the layered structure of the Southern Ocean is only marginally stable, isolated convection cells can form under the sea ice in many places. Why do only some of them lead to polynyas? The answer may have to do with spatial scale. When convection is triggered under a cover of sea ice, the initial burst of heat rising to the surface melts most if not all of the ice immediately above the cell. This creates a film of fresh water at the surface. The fresh water is less dense than the warm salty water, and so it is stable: it damps out the convection, because the warm water cannot rise past it to the surface. Even if that initial sheet of fresh water were not sufficient to damp out the convection, other sections of ice would flow into the polynya and melt, perhaps eventually providing enough fresh water to halt the convection.

If the polynya initially had a large area, however, it could be self-sustaining. The surface area of a polynya, within which convection occurs, is proportional to the square of its radius. The amount of ice that can float into a polynya is proportional to its perimeter, which is directly proportional to the radius. Thus if a polynya had a radius above some minimum threshold, ice could not flow in quickly enough to stop the convection and the polynya would survive.

For reasons that have to do with the fluid dynamics of the rotating earth, the convection cells in the Southern Ocean cannot have a diameter greater than about 10 to 30 kilometers. A large, self-sustaining polynya would therefore probably have to consist of a number of convection cells pressed together "shoulder to shoulder."

Sensible-heat polynyas have a number of important effects. For one, their convection cells draw up warm water from the Circumpolar Deep Water and accelerate the process in which heat is transferred to the atmosphere. It is not yet known how important this effect is in the overall action of the global heat engine, because it is not known whether large polynyas form frequently enough to be climatically significant. The effect could be substantial, however, because the ocean sheds heat from open water so much more efficiently than through ice.

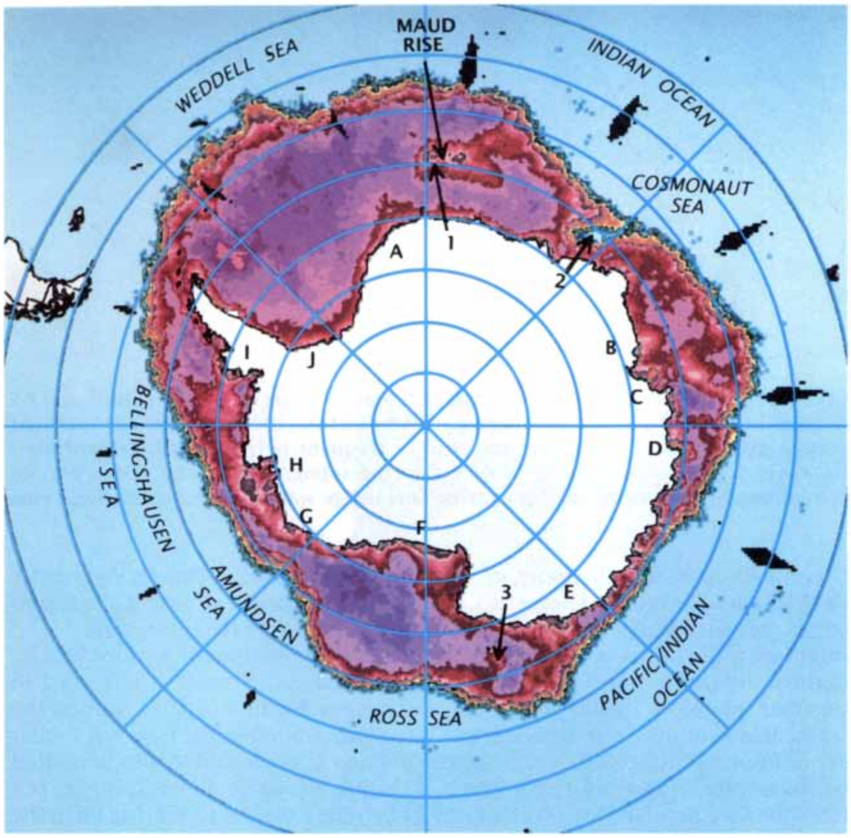
Sensible-heat polynyas also promote chemical interaction between the ocean and the atmosphere. Unlike water under the ice pack, water exposed in a polynya can exchange gases relatively freely with the atmosphere, absorbing some and releasing others, before it sinks again. Although the rapid rate of overturning within a polynya would prevent any specific water parcel from attaining full equilibrium with the atmosphere, it would still allow significant exchange of gases. The existence of large sensible-heat polynyas could thus alter the nature of the ocean-atmosphere interaction and thereby have a great effect on the chemistry and climate of the atmosphere and the deep ocean worldwide.

Much of our knowledge concerning open-ocean polynyas has come from studying one spectacular polynya that formed in the mid-1970's near the Weddell Sea. The Weddell Polynya was remarkable for several reasons. One reason was its sheer size: at its largest it measured some 350 by 1,000 kilometers.

Another remarkable feature was its persistence. It was first observed in the austral winter of 1974. During the following summer the ice cover in that region of the Southern Ocean melted completely, as it normally does, but when the ice cover formed again in the winter of 1975, the Weddell Polynya re-formed as well. It had moved slightly to the west (in keeping with the prevailing surface current in that region), but its shape and size were much the same as they were in 1974. The following year saw the same sequence of events: when the ice cover re-formed in the winter of 1976, the polynya reappeared, slightly to the west of its 1975 position and somewhat smaller.

In 1977 the Weddell Polynya did not appear, but its persistence over the three previous winters indicates the existence during the summer of some "memory" mechanism, some large-scale residual effect that could re-create the polynya after the summer melt. It is likely that the key to this memory mechanism is found in salinity. When the ice cover melted in the austral spring and summer, areas outside the polynya would have been covered by a thin layer of relatively fresh water. Because of its buoyancy, the fresh water would have stayed on the surface and not mixed with the water below. In the area where the polynya had been, however, the surface would have been salty, because there would have been no sea ice to melt there.

The following winter, when the cold atmosphere started to remove heat from the surface water, the layered structure of the waters in the region of the polynya would have become



POLAR VIEW reveals several open-ocean polynyas (*1–3*) and coastal polynyas (*A–J*). The image shows the average ice cover during a three-day span in the winter of 1980.

unstable: the salty surface water, on becoming colder and therefore denser, would have sunk and warmer water from lower layers would have risen, establishing new convection cells and re-creating the polynya. In other areas the relatively fresh surface water would simply have frozen, reestablishing the Antarctic ice cover.

The effects of the Weddell Polynya were in keeping with its size. The polynya left a clear imprint on waters far below the surface. For example, measurements of temperature at various depths made in the area of the polynya during the summers of 1973 and 1977 (that is, before and after the occurrence of the polynya) reveal dramatic changes in the temperature of the deep water. The changes seem particularly dramatic when one bears in mind how very stable the deep waters of the ocean are over short time scales. The temperatures measured in the region in 1977 were colder than those measured in 1973 by as much as .8 degree, in depths all the way down to 2,500 meters.

The missing heat had probably been carried to the surface by convection in the polynya. Reasonable estimates suggest that the rate of convective overturning necessary to transfer that much heat could have been as high as six million cubic meters per second during the winter, when the polynya was active. In the process the polynya could have produced as much as half of the Antarctic Bottom Water that flowed out of the Weddell Sea.

What caused the Weddell Polynya to form exactly where it did? The most plausible answer holds that the topography of the ocean bottom played a role. The polynya's first appearance was directly above a feature called the Maud Rise, which is an underwater seamount. Here the bottom is some 3,500 meters closer to the surface than it is in other regions. Perhaps the warm Circumpolar Deep Water is deflected toward the surface as it passes over the Maud Rise. This would "precondition" the region so that other events, such as greater than average mixing of the water by windstorms, would be more likely to bring warm, salty water into the surface layer, triggering the formation of convection cells.

Satellite data from the years since 1976 yield some evidence for the hypothesis. In many of those years the microwave measurements reveal relatively small polynyas or areas of very thin and patchy ice cover in the vicinity of the Maud Rise. Further evidence is found in an area called the Cosmonaut Sea near 65 degrees south latitude and 45 degrees east longitude, where the ocean circulation, perhaps in response to the topography of the bottom, also seems to be preconditioned for the formation of convection cells. In the Cosmonaut Sea, as over the Maud Rise, small polynyas and areas of diminished ice cover often occur. These polynyas in general do not survive an entire winter.

To test this hypothesis, one of us (Gordon) helped organize efforts to push through the ice cover and reach the Maud Rise region in winter. Our first attempt was in 1981 on the Soviet ship *Mikhail Somov.* On this trip we were not able to penetrate all the way to the Maud Rise, although we got close enough to be able to gather extremely useful data on the interactions between the deep water and the surface layer below the ice cover. We found an unexpectedly large entrainment of deep water into the winter surface layer, suggesting an active vertical flux of deep water.

We succeeded in reaching the Maud Rise on our next attempt, in the austral winter of 1986, as part of a multinational expedition on the West German vessel *Polarstern* of the Alfred Wegener Institute for Polar and Marine Research in Bremerhaven. Although the analysis of our data from that expedition is incomplete, we found there was indeed an upwelling of deep water over the Maud Rise. The fact that there was an upwelling in 1986, even in the absence of a polynya, indicated that the topography of the ocean bottom was probably deflecting the flow of Circumpolar Deep Water upward. In addition to elucidating mechanisms associated with the formation of the Weddell Polynya, the *Polarstern* voyage represents a relatively new and exciting way to study the ocean: combining large-scale satellite observations of the surface with local, ship-based research.

The study of polynyas is leading oceanographers to a new understanding of the mechanisms at work in the Southern Ocean. As a result it is bringing about new ways of considering the processes that govern much of the world's climate, and it raises important new questions. For example, does the overturning in large polynyas, such as the Weddell Polynya, alter the rate at which carbon dioxide is exchanged between the ocean and the atmosphere? The deep water that wells up south of 60 degrees south latitude is high in carbon dioxide and releases significant quantities of it to the atmosphere. Because polynyas accelerate the upward flux of Circumpolar Deep Water, one might expect they would enhance the rate of carbon dioxide release, perhaps adding to the projected global greenhouse warming. On the other hand, as we mentioned above, the rate of overturning in polynyas is so great that no single water parcel spends enough time near the surface to exchange much carbon dioxide with the atmosphere. The net effect of polynyas on atmospheric carbon dioxide levels is therefore uncertain. Conversely, it is also not known what effect the projected warming might have on the frequency or extent of future polynyas.

How important are polynyas generally in the deep-ocean overturning that takes place in the Antarctic? We know the Weddell Polynya had quite a pronounced effect, cooling a great volume of ocean and giving surface water access to the atmosphere over a large area. Are such large polynyas rare events, or do they occur relatively often? And how much of the overturning that takes place near the continental shelf is mediated directly by the coastal polynyas? Oceanographers now have the tools to answer these important questions and many others. The combination of comprehensive, long-term observations by satellite and detailed observations from the field in winter is making it possible to construct ever more precise models of these vital and far-reaching processes in the Southern Ocean.

FURTHER READING

WEDDELL DEEP WATER VARIABILITY. Arnold L. Gordon in *Journal of Marine Research,* Vol. 40, Supplement, pages 119-217; 1982.

ANTARCTIC SEA ICE, 1973-1976: SATELLITE PASSIVE-MICROWAVE OBSERVATIONS. H. Jay Zwally, Josefino C. Comiso, Claire L. Parkinson, William J. Campbell, Frank D. Carsey and Per Gloersen. NASA Special Publication 459; 1983.

ANTARCTIC OFFSHORE LEADS AND POLYNYAS AND OCEANOGRAPHIC EFFECTS. H. Jay Zwally, Josefino C. Comiso and Arnold L. Gordon in *Oceanology of the Antarctic Continental Shelf,* edited by Stanley S. Jacobs. American Geophysical Union, 1985.

RECURRING POLYNYAS OVER THE COSMONAUT SEA AND THE MAUD RISE. J. C. Comiso and A. L. Gordon in *Journal of Geophysical Research,* Vol. 92, No. C3, pages 2819-2833; March 15, 1987.