SEA ICE Observations

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SEA ICE AND CLIMATE

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Sea ice and climate overview

Each winter the surface of a large area of the Southern Ocean freezes, forming a sea ice cover that surrounds Antarctica. This ice, with its expansive maximum extent and large annual variability, has a major influence on the global climate system. The Antarctic sea ice cover affects the transfer of heat, mass and momentum between the ocean and atmosphere. This, in turn, affects both atmospheric and oceanic circulation.

The ice acts as a physical barrier to the exchange of gases (such as oxygen, carbon dioxide and water vapour) and as an insulating blanket between the relatively warm ocean and colder atmosphere. During winter when the temperature gradients between the surface ocean and the atmosphere are greatest, the loss of heat to the atmosphere can be up to two orders of magnitude smaller over a sea ice cover than over open ocean. With its high albedo (the fraction of incident solar radiation that is reflected by the surface) the ice and its snow cover also reduce the amount of incoming solar radiation absorbed at the ocean surface. The transfer of momentum from the atmosphere to the ocean, which influences ocean currents, is also modified by the presence of ice.

Sea ice is considerably less salty than sea water, and salt rejected from the ice during its formation and growth increases the salinity and density of the underlying water. This may induce deep vertical convection that contributes to the upwelling of nutrients and to the overall thermohaline circulation (water movement driven by salinity and temperature gradients) of the ocean. Conversely when the ice melts in spring it releases fresher water, forming a stable low salinity surface layer.

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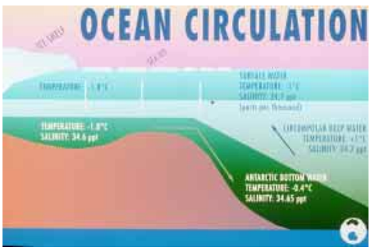

Schematic of ocean circulation in the Antarctic sea ice zone

The Antarctic sea ice zone is a habitat for many species of biota. Many algal communities reside within or

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under the ice, and algal blooms occur in the stable freshwater "lens" that forms as the ice edge retreats in the summer. Large quantities of krill feed on the phytoplankton that in some way depend on the sea ice and in turn provide a major food source for larger animals such as whales, seals and penguins. The sea ice is also used as a breeding platform by some seals and penguins and may provide a refuge from predators.

Even in winter only a small fraction of sea ice close to the Antarctic continent occurs as a continuous and uniform sheet. This ice, called "land fast" ice, is pinned to the coast and does not move. The majority of the ice occurs in a wide band around the continent and is referred to as "pack ice".

This is a region of highly variable ice conditions and contains a range of ice types with varying floe size, age and thickness that is present in varying concentrations. The pack is highly mobile, moving with the wind and currents, and its characteristics are constantly changing. Open water (leads) is frequently found between the floes and it is common to see ice at various stages of development present in the same area. This is the result of the dynamic nature of the pack, with the thickness of floes increasing through rafting and ridging as they interact. New open water areas are constantly being created allowing new ice to form.

The degree to which sea ice affects ocean-atmosphere interaction depends on the ice extent and its thickness distribution. The thickness distribution describes the pack ice cover in terms of the concentration (ie the fraction of surface area covered) of different ice thickness categories.
While sea ice influences the ocean and the atmosphere, the distribution and characteristics of the ice are, in turn, forced by atmospheric and oceanic variables such as temperature, wind, ocean currents and swell. Thus, the ocean, sea ice and atmosphere form a complex interactive system.

The extent and variability of Antarctic sea ice

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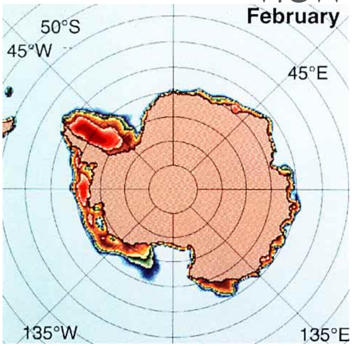

February is the month of minimum sea ice extent around Antarctica. This is a composite SSM/I image for February.

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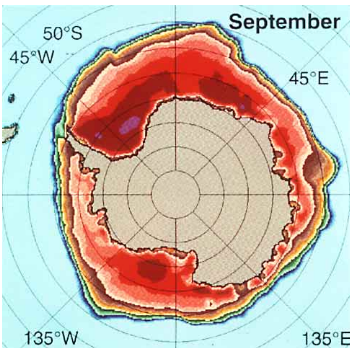

September is the month of maximum sea ice extent around Antarctica. This is a composite SSM/I image for September.

figures reproduced from Gloersen et al (1992)

The Antarctic sea ice zone undergoes one of the greatest seasonal surface changes on Earth.
On average it expands from a minimum extent of 4 million square kilometres in February to a maximum of 19 million square kilometres in September.
At maximum extent the area of sea ice is greater than the area of continental Antarctica.

The latitude of the ice edge varies around Antarctica and also exhibits a large amount of inter-annual variability. Cyclonic ocean currents in the embayments of the Ross and Weddell Seas and Prydz Bay influence the drift and distribution of ice in those regions. The pack ice associated with the Weddell Sea gyre extends further north than anywhere else around the continent, and at maximum extent may be up to 2200 km from the coast. In contrast, the East Antarctic pack may only extend to a few hundred kilometres from the coast in some places, such as between 120–135°E. This is primarily because the East Antarctic coast extends further north than many other areas of the Antarctic (except the tip of the Antarctic Peninsula) and is climatologically warmer.

On a shorter time scale, the position of the ice edge may change by tens of kilometres per day due to the passage of synoptic weather systems and the associated changes in wind direction.

Differences between Antarctic and Arctic sea ice

There are a number of fundamental differences between Arctic and Antarctic sea ice as a result of geographical differences between the two polar regions.

The Antarctic sea ice zone is unbounded at its northern extent and, as a result, the pack ice is highly dynamic and undergoes cyclical periods of convergence and divergence due to changing winds and ocean currents. North of the Antarctic Divergence the pack generally moves from west to east in the southern limit of the Antarctic Circumpolar Current, but with a net northward drift.

The unconstrained nature of the Antarctic pack results in a large seasonal variability in extent, and very little ice survives more than one melt season.

In contrast, the Arctic basin is predominantly land-locked, with only a small fraction of ice advected equatorward out of the region of production, mostly via Fram Strait between Greenland and Svalbard. Arctic sea ice thus exhibits less annual variability in extent, and retains a greater proportion of multi-year ice. Because of its constrained nature and greater age, Arctic sea ice attains a greater average thickness than sea ice in the Antarctic, with multi-year ice commonly up to several metres thick (even a few tens of metres thick in heavily ridged areas) and up to several decades old.

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Undeformed first-year sea ice in the Antarctic rarely reaches thicknesses greater than two metres, and only then in fast ice regions close to the coast.

Within the Antarctic pack, frazil crystals which form in open water areas make a major contribution to the total ice mass. The dynamic processes of rafting and ridging are the dominant mechanisms by which the ice thickens. As sea ice in the Arctic Basin is not as mobile, fewer open water areas occur and frazil ice growth makes a smaller contribution to the total ice mass.

Another major difference between Arctic and Antarctic sea ice is observed during the respective melt seasons.

In the Arctic the sea ice begins to melt at the surface. Melt pools form and decrease the albedo of the surface, allowing more solar radiation to be absorbed and further enhancing the melt process. In the Antarctic melt occurs mainly from the bottom and sides of floes, which are in contact with the ocean. Melt pools are rarely seen on the surface. Divergence of the pack creates more open water and as summer approaches more solar radiation is absorbed by the ocean. As the surface layer of the ocean warms, the rate of ice melt increases. Closer to the coast the low relative humidity of the air flowing off the Antarctic continent causes surface ablation to occur via direct sublimation of the ice to water vapour.

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Observing Antarctic sea ice

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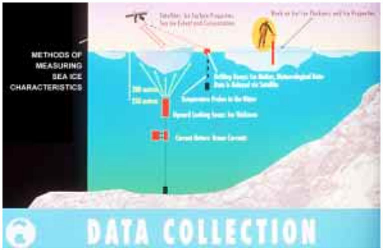

Data collection methods in addition to ship-based observations.

Sea ice research utilises information from a number of sources. These include satellite imagery, aerial photography, drifting buoy measurements, data from moored instruments, ship-based observations, and in-situ measurements.

The development of satellite imagery has dramatically increased our knowledge of Antarctic sea ice.

With the large spatial coverage and relatively high temporal resolution of satellite imagery the position of the ice edge can be tracked closely.
Ice concentration and information on the nature of the ice surface may also be obtained from satellite data, and a climatology of sea ice extent and concentration is being accumulated, providing a valuable tool for monitoring any change in sea ice conditions.

Satellite data, however, provide little or no information on the thickness of the sea ice, an essential parameter for understanding ocean-ice-atmosphere interaction and for determining the mass balance of the sea ice zone. Hence, information on many ice thickness and other characteristics of sea ice can only come from direct in situ observations. Data can also be collected from vessels moving through the sea ice as described in the "ice obs" tutorial on this CD ROM. Information is recorded on the ice types present, their concentration, thickness, floe size, topography and snow cover.

In situ measurements of the sea ice and snow characteristics are necessary for studying the structure of the sea ice, determining its history and for ground truthing remotely sensed data. This is done by drilling holes through the ice, taking ice cores, and digging snow pits (as shown in the photographs on the next page). Analysis of the crystal structure of the ice cores reveals how the ice was formed, and subsequently deformed, and what contribution each ice type makes to the total sea ice mass.

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Samples are taken from snow pits to analyse grain size, density, salinity and oxygen isotope composition.

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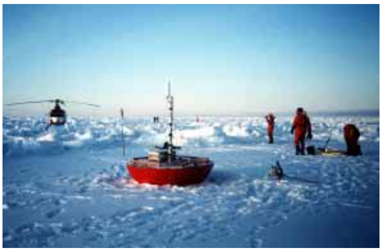

Drifting buoys tracked by satellite systems and deployed on or between ice floes allow the drift of the Antarctic pack to be measured.

On the time scale of hours to days the divergence and convergence of the pack may be observed, while buoys tracked for longer time intervals show the larger scale motion of the pack under the influence of the prevailing winds and ocean currents.

Sea ice formation processes

The first stage in sea ice development is the formation of individual ice crystals in the surface layer of the ocean. These crystals, known as frazil, form in open water areas when the temperature of the water is below -1.8°C.

Frazil ice gives the water an oily appearance and, with further freezing, the crystals coagulate to form a soupy layer at the surface known as grease ice.

Further development of the sea ice cover is determined by atmospheric and oceanic conditions. Under calm conditions the frazil and grease ice may consolidate to form continuous flexible sheets

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called nilas. Nilas may be up to 10 cm thick, but is easily rafted under pressure and can rapidly increase in thickness. Ice 10–30 cm thick is termed young ice and with further growth or rafting and ridging it develops into first-year ice (>30 cm). Finger rafting is a common process observed in nilas where interlocking fingers of ice are thrust alternately over and under each other where two sheets of nilas converge.

A common process of sea ice development in the Antarctic, which occurs under rougher conditions, is the "pancake cycle". With the influence of wind and wave action the frazil crystals coagulate, eventually consolidating into small circular discs of ice called pancakes. The pancakes may have raised rims caused by collisions with other pancakes.

By rafting and bonding together the pancakes may rapidly increase to a few metres in diameter and up to 40 cm thick, and eventually freeze together to form larger floes or a consolidated ice cover.

Although new ice forms most rapidly in open water areas with the development of frazil crystals, ice also grows on the underside of existing floes as oceanic heat is conducted from the ice-water interface through the floe. This ice is called congelation ice and consists of characteristic long columnar crystals which form by slow thermodynamic growth, distinct from the small randomly oriented crystals of frazil ice.

New ice may also be formed from the freezing of flooded snow overlaying the sea ice.

When the weight of the snow is sufficient, the ice surface may be depressed below sea level. The influx of sea water through the permeable snow saturates the lower layers of snow which may subsequently refreeze to form "snow-ice".

Snow-ice has a similar texture to ice formed from coarse grained frazil but may be discriminated from frazil by stable isotope analysis. Compared with sea water, Antarctic snow is relatively depleted in the heavy stable isotope, ^{18}O, and therefore has a highly negative $\delta^{18}O$ value.

Results from the East Antarctic pack have revealed that on average the pack is comprised of 39% columnar ice, 47% frazil ice and 13% snow-ice, with other ice types making up the remaining 1%. These figures indicate the importance of the dynamic processes within the pack which favour the growth of frazil ice. Snow-ice also makes a significant contribution to the total ice mass of the region.

Sea ice drift and deformation

Sea ice drift

Sea ice drift is one of the most important features of the Antarctic pack ice zone. Because the pack is unconstrained by land it is highly mobile, with the speed and direction of ice drift dependent on the winds and ocean currents.

The nature of the ice drift is most important in determining the sea ice thickness distribution, which in turn determines the degree of interaction between the ocean and the atmosphere. The net drift of the pack is divergent, but frequent periods of convergence cause floe deformation.

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Divergence of the pack is commonly associated with southerly winds which cause the ice to be advected northward. This creates open water areas between the floes, allowing rapid ice growth (in the form of frazil) to occur in these areas. Northerly winds cause the pack to converge, increasing the ice concentration and thickening the ice by rafting and ridging. The passage of low pressure systems causes the pack to undergo cyclical periods of convergence and divergence due to fluctuating wind direction.

The characteristic pattern of ice drift in the East Antarctic is westward near the continent and eastward north of the Antarctic Divergence. Data from 45 satellite-tracked buoys deployed between 1985 and 1997 have shown that the mean drift speed in the westward flow is 0.22 m s^{-1} (19.4 km d^{-1}), and 0.17 ms^{-1} (14.9 km d^{-1}) in the eastward flow. Ice drift speeds are highly variable both spatially and temporally. Over short time intervals, speeds of up to 0.90 m s^{-1} (78 km d^{-1}) have been measured.

Persistent katabatic winds which drain off the continent maintain open water areas in the form of coastal polynyas by advecting newly formed ice northwards. These polynyas act as "ice factories" and make a disproportionately large contribution to the total ice mass of the pack per unit area.

The importance of ice drift to the sea ice thickness distribution is evident in the ice core analysis mentioned previously, where the mean percentage of frazil crystals comprising the East Antarctic pack was found to be 47% - almost half of the ice mass for that region. This is in stark contrast with the Arctic, where frazil ice comprises only about 5% of the total ice mass.

Rafting and ridging

Structural analysis of ice cores from the Antarctic pack indicate that the dynamic processes of rafting and ridging play a major role in the development of Antarctic sea ice, and significantly affect the sea ice thickness distribution. Rafting and ridging occur when floes converge and collide as a result of the differential drift of individual floes.

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Rafting in the early stages of ice development is often responsible for the rapid thickening of floes to about 0.4–0.6 m. It is predominantly through rafting that nilas develops into young ice, and small pancakes are stacked to form larger floes. Convergence of floes greater than approximately 0.4–0.6 m thick is more likely to result in pressure ridging.

An estimate of the areal extent and height of ridging is included in the routine sea ice observations made from ships. This is important since ridges contain a disproportionately large percentage of ice mass per unit area. For example, ship-based field data from the East Antarctic pack shows that when the ridged areas are taken into account, the mean ice thickness increases by an average of 1.7 times the mean undeformed ice thickness. As the total ice volume is the key parameter for determining the amount of salt rejected from the ice during the growth season, and the amount of fresh water released during the melt season, any estimate of average ice thickness needs to incorporate the contribution of ridges.

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