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# The great ice mystery

**Changes in the extent and thickness of sea ice could alter ocean circulation and so disrupt the climate. Jon Copley considers one of the big unknowns in the global warming debate.**

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**Chill out: the bestiary of ice ranges from the small ice flowers that form on sea ice (top) to the large chunks of pancake ice that bond to form floes. The dynamics of sea ice are now coming to light.**

Contrary to popular myth, the Inuit do not have dozens of words for snow. Oceanographers, however, do have a multitude of terms for sea ice — including frazil, grease, shuga, pancakes and brash. Each describes a different stage in the freezing of surface sea water.

This shifting frozen skin is a crucial boundary between the oceans and the atmosphere. It regulates the transfer of heat, and gases, and is a vital part of the 'engine' that drives the circulation of the world's oceans. Given that changes in this circulation could have profound effects on climate — plunging Western Europe into the deep freeze while most of the world warms, for instance — a better understanding of the dynamics of sea ice is becoming a top priority.

Fortunately — thanks in part to the declassification of data gathered by military submarines during the Cold War — the necessary information is starting to come to light. Even so, researchers investigating sea ice have their work cut out, if they are to assist the modellers who are trying to anticipate the effects of climate change — and so help politicians decide how to respond to the challenges ahead. "We now have a fairly massive data-processing task," says Peter Wadhams of the United Kingdom's Scott Polar Research Institute in Cambridge.

Salt water has a lower freezing point than fresh, so sea ice usually begins to form when the temperature of surface water drops below −1.8 °C. This process is quite distinct from the creation of icebergs, which happens when glaciers meet the sea. At first, tiny crystals known as frazil appear; these then coagulate into a soupy slick known as grease. If conditions are calm, grease ice can grow into a thin, elastic crust called nilas, which may thicken into more substantial cover. More often, wind and waves push grease ice into pancake-shaped chunks that eventually bond to form floes.

Sea ice may continue to congeal on the underside of existing floes, or even form on their upper surfaces if the the weight of accumulating snow pushes the floes below sea level. Colliding floes can be squeezed into thick ridges. And although much of the ice melts away each summer, some survives to accumulate new growth in subsequent years. As a result of all these processes, sea ice can take a multitude of forms — hence the exotic names devised by its aficionados.

## Poles apart

The yearly cycle of freezing and thawing differs between the poles. The largely landlocked Arctic Ocean offers fewer opportunities for sea ice to drift to warmer latitudes, and so retains a greater proportion of multi-year ice. Melting in the Arctic tends to begin at the surface, producing pools of melt water that may absorb more heat and promote further melting. But melt pools are rare in the Antarctic, where melting ice can more easily break up, exposing areas of open water. This allows greater heating of the surface ocean, which melts the sides and bottom of remaining floes. Little ice survives more than one year in the waters around Antarctica, and as a result the seasonal extent of the ice is much more variable than in the north. Consecutive satellite images of sea ice around the continent reveal a pulsating halo that waxes and wanes with the seasons.

In addition to this seasonal cycle of growth and decay, the extent of sea ice seems to vary over longer timescales. In recent years, there have been several signs that sea ice has receded in the Arctic. Data from satellite passive-microwave observations — which, by recording thermal radiation from the Earth's surface, allow sea ice to be distinguished from open water — reveal that between 1978 and 1996 the average overall extent of Arctic sea ice shrank by around 34,000 square kilometres per year, or 2.8% per decade[1]. The season during which there is a net melting of sea ice also appears to have lengthened by 8% per decade over the same period[2].

The extent of ice is not the whole story, however. "Satellites see ice extent very well, but it's a little harder for them to figure out how thick the ice is," says Drew Rothrock of the University of Washington in Seattle. But the submerged depth of ice, or ice draft, can be measured from below using sonar. To get these data, Rothrock has been on Arctic cruises aboard US Navy submarines as part of a programme called Scientific Ice Expeditions (SCICEX). The programme also has access to recently declassified ice-draft data collected by submarines during the Cold War.

SCICEX cruises in the 1990s measured a mean ice draft of 1.8 metres above the deep waters of the Arctic north of Canada at the end of each melt season. In contrast, submarine patrol data from 1958 to 1976 show that the mean used to be 3.1 m (ref. 3). "It's a terrific record and it's only just being made public," says Rothrock. "We're trying to get more data into the public archive."

## Thinning on top

Meanwhile, British submarines have charted a complementary record of changes in ice thickness in other regions of the Arctic. "We're finding the same amount of thinning in summer on the European side as Rothrock found on the Canadian side," says Wadhams, who cruised in Royal Navy submarines in 1971, 1976, 1987 and 1996[4]. This year, the UK Hydrographic Office released data on cruises from 1988 to 1995, filling gaps in Wadhams's record. He is now scrutinizing the record to see whether there was steady thinning over the period, or whether most of it happened in one go.

The big question is whether the changes in Arctic sea ice are a consequence of global warming. General circulation models (GCMs), which modellers use to probe the effects of rising levels of greenhouse gases, predict that global warming should be enhanced in the Arctic. This may be amplified by a mechanism known as ice-albedo feedback. Sea ice is highly reflective, particularly when it is covered with snow. So less sea ice means that less solar radiation is reflected, and the sea absorbs more energy, enhancing local warming and promoting further melting. Disappearing sea ice may therefore hasten its own demise by exposing more open water to the Sun.

This positive feedback can work the other way, with growing sea ice promoting the formation of yet more ice — particularly when it extends far from the poles. Indeed, during the late Proterozoic era, between 600 million and 800 million years ago, such a runaway effect may have encased most of the planet in ice — creating a 'snowball Earth'[5].

Sea ice cover may oscillate naturally over timescales of decades or longer. But researchers do not know whether the present decline in the Arctic can be explained by such oscillations or whether it is a direct result of the build-up of greenhouse gases in the atmosphere. Another possibility is that the changes in ice cover are being driven not by a slow increase in air temperature, but by changes in ocean circulation. "It's possible that most of the thinning happened from 1990 onwards, because that's the time when there's been a change in the oceanographic conditions in the Arctic," says Wadhams. In the past decade, he points out, there has been more warm water flowing into the Arctic from the Atlantic.

Meanwhile, at the other end of the world, the jury is still out on what effect increased atmospheric carbon dioxide will have on sea ice. Some GCM simulations predict a very slow warming of surface air[6], but others predict more rapid changes that would cause the extent and thickness of sea ice to be drastically reduced[7]. So far, satellite data show no signs of a reduction in the overall extent of Antarctic sea ice.

## View from the bridge

But down south, it is hard to monitor ice thickness, because the Antarctic Treaty forbids military submarine cruises. To fill in the picture, the Antarctic Sea Ice Processes and Climate (ASPeCt) programme of the Scientific Committee on Antarctic Research is compiling observations of sea ice made from ships between 1980 and 1997[8]. Because different categories of sea ice can be used as a proxy for ice thickness, observations of ice type — typically made every

Packed in: the *Des Groseilliers* spent a year frozen into the Arctic ice as a research station.

hour from a ship's bridge — can be translated into estimates of ice thickness. So far, the ASPeCT data comprise 11,000 observations from 42 voyages.

The programme expects to release the first circumpolar distribution of sea ice thickness compiled from these records early next year. As part of the ASPeCt programme, Tony Worby of the NASA Goddard Space Flight Center in Greenbelt, Maryland, has produced a CD-ROM to train observers to make consistent records during future Antarctic voyages. These records will be added to an archive at the Antarctic Cooperative Research Centre in Hobart, Tasmania, to provide a long-term time series of ice thickness estimates.

Programmes such as ASPeCt and SCICEX should, over the next few years, allow researchers to begin to understand how global warming is affecting sea ice cover. But if sea ice is receding, what are the consequences?

## Failing circulation

For commercial shipping, a reduction in ice cover could bring benefits. This summer, the Royal Canadian Mounted Police patrol vessel *Nadon* (temporarily rechristened the *St Roch II*) made a transit through the Northwest Passage — the shortcut between the Pacific and the Atlantic across the top of North America — and encountered very little sea ice along the way.

But changes in ice cover could have far-reaching effects on climate. When surface sea water freezes, its dissolved salt is left behind, forming a cold, dense brine that tends to sink. This mixes with the water below in a process known as deep water formation, which is an important part of the thermohaline circulation — the conveyor belt of ocean currents that spreads heat around the globe and has a strong influence on climatic conditions. Indeed, some researchers believe that sea ice variability may cause the switch between ice ages and interglacial periods.

Wadhams is involved in a project over the next three years to examine the interaction between sea ice and the thermohaline circulation in the Greenland Sea. In this area, the Odden ice tongue — a seasonal sea ice feature that sticks out from the coast of Greenland — has failed to form in five of the past seven years[9]. If the loss of the ice tongue is slowing the formation of deep water, it could seriously disrupt the thermohaline circulation in the North Atlantic. Potentially, it could weaken the flow of warm water from the Gulf of Mexico that currently ensures that northwest Europe enjoys a much milder climate than its latitude would otherwise allow.

Modellers have only recently begun a concerted effort to examine the effects of changing sea ice cover on the thermohaline circulation. One of the first of these studies suggests that the extent of sea ice and the strength of the thermohaline circulation could oscillate gently over the decades[10]. Other studies indicate that there may be destabilizing feedbacks that could weaken the thermohaline circulation[11,12]. Jochem Marotzke of the Southampton Oceanography Centre, a co-author of one of these studies, believes the models must be improved to make better use of existing knowledge of sea ice processes.

**On thin ice: one of the *Des Groseilliers*'s crew measures the extent of melting in the Arctic.**

## Go with the floe

To check the validity of existing models, the National Science Foundation and the Office of Naval Research funded an experiment called SHEBA — the Surface Heat Budget of the Arctic. Led by Don Perovich of the US Army's Cold Regions Research and Engineering Laboratory in Hanover, New Hampshire, the SHEBA team let the Canadian icebreaker *Des Groseilliers* freeze into the Arctic ice pack to provide the headquarters for an ice station.

The ship and the cluster of tents around it drifted 640 kilometres across the Arctic with the pack ice for a year from October 1997. During this period, the ice station's crew conducted an intense series of atmospheric, oceanographic and ice observations over a floe that initially measured roughly eight kilometres square — chosen to be about the same size as the individual computational cells that make up a typical GCM.

One of the SCICEX submarine cruises also buzzed the SHEBA site during the experiment to check the team's measurements of ice thickness. One of the key findings of SHEBA was that the sea ice was less than two metres thick to start with, but ended up even thinner at the end of the experiment, despite undergoing a full annual cycle of growth and melt. Full results from the programme are expected to appear next year in a special issue of the *Journal of Geophysical Research — Oceans.*

The SHEBA team also carried out many studies of small-scale changes in sea ice, which together suggest that the devil may be in the details. Hajo Eicken of the University of Alaska in Fairbanks examined the growth of meltwater ponds on the surface of the ice during summer. Meltwater pools are less reflective than snow-covered ice, allowing them to absorb more heat and grow. But if this causes the formation of channels that allow water to drain through into the ocean, bare ice will be exposed once again. So tiny flaws and channels in the structure of sea ice may be critical in determining the amount of solar energy absorbed by the Arctic in summer.

"This illustrates how the refinement of models involving sea ice depends on results from studies of sea ice and sea ice processes at very small scales," says Eicken. "Our improved understanding of how the plumbing system works may allow us to assess whether this is a process that large-scale climate modellers need to worry about."

As the world's government's grapple with the issue of climate change, those studies could prove crucial. For until the ocean's icy skin reveals the full extent of its subtleties, those attempting to forecast our future climate could be shooting in the dark. ■

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