Melting ice sheets

Scientific certainties and uncertainties

The Antarctic is a remarkable continent – remote, hostile and uninhabited. Yet it is of key importance to our understanding of how the world works. It is a place of extremes. Almost 60 times the size of the United Kingdom, Antarctica is the highest, coldest and windiest continent. Less than 1% of it is free of ice or snow. The ice cap, which shrouds the peaks and valleys of the continent, contains almost 70% of the world's freshwater and 90% of the world's ice. During winter the ocean surface freezes, forming a cover of sea ice as large as the continent it surrounds.

Snow falls across Antarctica and is slowly compressed into ice, forming massive sheets up to 4.5 kilometres thick. Ice sheets flow as glaciers towards the coast, extending into the sea as floating ice shelves. Ice melts from the bottom of the ice shelves and icebergs break off from their edges. If gains from snowfall and losses from melting and breakage are balanced, the ice sheet is in equilibrium. If the rates of snowfall, melting, or iceberg calving change, this pushes the system out of equilibrium, causing the ice sheet to thicken or thin.

Since the 1950s, the floating Wordie and Larsen ice shelves that fringed the Antarctic Peninsula have retreated or collapsed. These changes are probably the result of recent climate warming, amplified over the Antarctic Peninsula. But thinning glaciers further south may be telling a quite different story.

Satellite measurements show us the ice is getting thinner at Pine Island and Thwaites glaciers, part of the West Antarctic Ice Sheet. This thinning peaks where the grounded glacier begins to float, and the pattern of thinning extends up to 150km inland. We are not yet sure exactly what is causing this thinning and what the implications are, but scientists, funded by the Natural Environment Research Council (NERC), are working to answer different aspects of these questions. They are trying to establish the relative importance of three possible drivers of the thinning. Is this another result of recent climate change? Is it a continuing response to the great glaciation that occurred 18,000 years ago? Is it complexities in ice flow that we're only beginning to understand?

Why do we need to know? If the West Antarctic Ice Sheet melts, the global sea level will rise by five metres.

Here we describe the processes that affect the formation, stability and break up of ice shelves and sheets, and some of the technology we need to explore these remote and hostile environments.

Autosub

Autosub is an autonomous underwater vehicle that allows scientists to access the ocean beneath floating ice shelves. Its sensors measure water temperature and salinity and its sonars observe currents, the shape and depth of the seafloor and features beneath. With a range of several hundred kilometres, Autosub follows a predetermined course beneath the shelf, but decides for itself to turn back when its sonars tell it that the ice above and the seafloor below are converging. Autosub could play a crucial role in revealing the cause of ice sheet thinning. Sea ice conditions in March 2003 frustrated first attempts to travel under the Pine Island Glacier.

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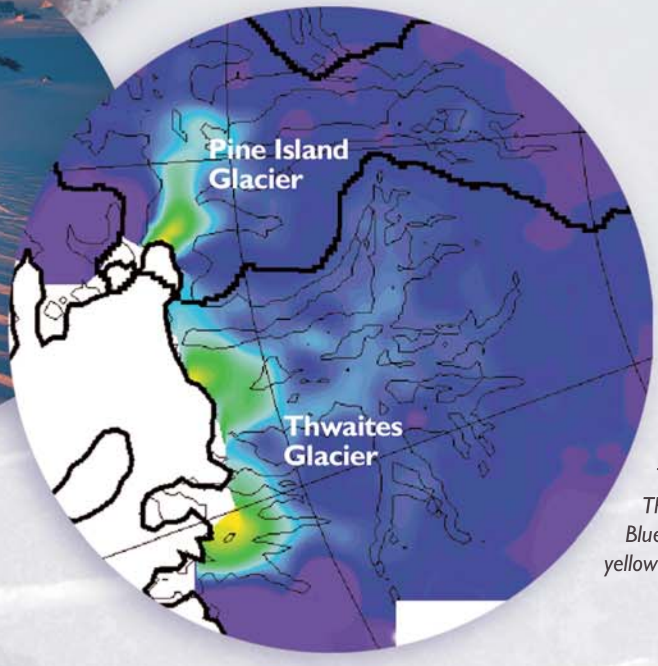
Ice Station ZERO

How do we know ice sheets are thinning?

The discovery that the West Antarctic Pine Island and Thwaites glaciers are thinning was announced in 2001. It was the culmination of a ten-year programme of continuous measurement of the Antarctic Ice Sheet, using radar echo soundings from Earth orbiting satellites. By combining the radar measurements with measurements of the orbits of the satellites, the height of the ice above sea level could be precisely determined. From 1992 to 2002 more than 10 million individual measurements were made. Each year the scientists mapped the changes in thickness since 1992. Gradually, the pattern of thinning in the Pine Island and Thwaites glaciers emerged.

We now have the promise of even finer details of glaciers flowing out of Antarctica. In 2004 a new generation of radar will be launched on the European Space Agency satellite CryoSat. This is designed to measure the steep, coastal regions of the Antarctic Ice Sheet.



Thinning of the Pine Island and Thwaites glaciers basins 1992 - 1998. Blue = no thinning, green = medium, yellow = fast thinning, up to 1.5m per year.

Is the thinning of Pine Island Glacier due to warming ocean waters?

Pine Island Glacier is 140km long. Half of its length covers the land as an ice sheet, and the other 70km extends out over the sea as a floating ice shelf. Beneath the shelf, ocean waters are just above 1°C, nearly 3°C warmer than elsewhere along the Antarctic coast. Because of this, the floating portion of Pine Island Glacier is melting more than one hundred times faster than most other ice shelves. The typical rate of ice shelf melt is around 10cm per year, but Pine Island Glacier ice shelf is melting at 10m per year. If the temperature of seawater beneath it were to rise by only 1°C, the rate of melting would double. This would lead to substantial thinning of the floating ice and eventually of the glacier inland. To understand whether such a change could be driving the thinning, we must understand what controls the water temperature beneath the shelf.

In the deep ocean basins surrounding Antarctica, warm water lies trapped between a chilled layer of bottom water and an even colder layer of surface water (-1.9°C). Centuries ago, this water was at the surface of the North Atlantic Ocean, but it has been carried south by global ocean circulation. Around most of the continent, this warm water never comes in contact with the ice sheet, but in the region around Pine Island Bay, the situation is different.

In March 2003, scientists using the NERC Autosub identified a tongue of water at 1.4°C heading towards Pine Island Glacier. A trough in the seabed, carved out by a glacier during the last ice age, provides a long narrow channel for this warm water to squeeze under the surface water towards the ice shelf. Could changes in this flow of warm water be responsible for the thinning of Pine Island Glacier?

We hope to find out just what role this tongue of warm water is playing in the delicate balance of ice and water in Pine Island Bay.

Ice Station ZERO

Is it a continuing response to earlier climate change?

Some 18,000 years ago, at the coldest time during the last glacial period, Pine Island Bay was filled with an ice sheet over a kilometre thick. This ice sheet was derived from the predecessor of Pine Island and Thwaites glaciers, which drained a major part of the West Antarctic Ice Sheet. Today, under warmer climatic conditions, the ice has retreated almost 400km to reveal the sea floor of Pine Island Bay.

Our marine-geophysical investigations at the edge of Pine Island Bay earlier this year demonstrate clearly that the glaciers once reached to the edge of the continental shelf where the seabed drops 2000m to the deep ocean. In the troughs across the continental shelf, fast-flowing glacier ice sculpted the sea floor into a series of long furrows. Mapping these features allows us to reconstruct the past direction of flow of the full glacial ice sheet.

The 400km retreat of ice from the outer part of Pine Island meant the loss of very large volumes of ice. The excellent preservation of sea-floor furrows from the last glacial period suggests that ice rapidly lifted off the sea floor as the climate warmed – slower retreat of grounded ice would have destroyed these delicate features. This implies that this retreat could have occurred by rapid break-up of a floating tongue or ice shelf. But the response of the inland parts of the ice sheet would have been much slower and may still be ongoing.

We are not sure whether the present melting from the ice shelf, and the production of icebergs, are a continuing retreat from the peak of 18,000 years ago or indicate a state of equilibrium with the present environment.

Is it the dynamic nature of ice?

The thinning of the Pine Island and Thwaites glaciers is not restricted to the ice shelf but extends deep into the ice sheet that covers the land. The changes inland may be following those in the ice shelf and may be caused by warm water reaching the shelf or a continuing retreat from the last ice age, as described in the last two sections. However, there is another possibility. The cause of the thinning may be associated with changes in the internal dynamics of the ice sheet. The thinning of the floating ice shelf may be following that of the interior, rather than vice versa.

We think of ice as a brittle material, like glass. However, when subjected to enough of its own weight, ice flows in a sluggish manner, rather like honey behaves. Ice is also lighter than water. These two properties together would cause the ice to spread out and thin until it was floating on the heavier ocean. Because the bed of the West Antarctic Ice Sheet is well below sea level, such a situation is possible, and is only avoided in practice because the snow, falling on the ice sheet, replaces the ice that floats away at the edges. Provided the snow fall balances the outward flow of ice, the ice sheet remains thick enough to rest on the bed beneath, and prevent the ocean from replacing the ice that is well below sea level. This situation is termed a 'dynamic equilibrium'.

Anything that may alter this equilibrium could cause the ice sheet to shrink. One possibility is that the flow of ice in the interior of the ice sheet is controlled by the friction between it and the land beneath. Because the Pine Island and Thwaites glaciers are flowing rapidly, we know that the ice melts at the bed, and that liquid water is controlling to some extent the bed friction. In addition, the ice (like honey) flows more easily when it is heated. These processes may all interact: frictional heating of the ice may cause more flow and more melting, thereby thinning the ice. On the other hand, increased flow may bring colder ice near to the bed, reducing the flow and causing the ice to thicken again.

To investigate these possibilities, we are using computers to model the flow of the Pine Island Glacier. We are using the models to examine what happens when a change is made that may alter the dynamic equilibrium. We can examine what changes may occur in the flow due to increased melting at the base near the grounding line, a rise in sea level, or internal changes at the bed. These may be compared with the actual pattern of thinning revealed by the satellite measurements. In this way, we hope to distinguish whether the thinning of Pine Island and Thwaites glaciers may be explained by changes in the surrounding ocean, or whether the fluid dynamics of ice are also implicated in the present retreat. We need to know what is driving the thinning if we are to predict the evolution of the ice sheet.