www.iop.org/journals/physed

Exploration glaciology: radar and Antarctic ice

H D Pritchard and R G Bingham

British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK

Abstract

The Antarctic ice sheets hold a huge reservoir of ice in a dynamic cycle fed by falling snow and drained by glaciers and ice streams. In order to predict future changes to sea level, it is vital to measure the ice sheet volume, to monitor changes in glacier flow and thickness, and to attempt to reconstruct the history of ice sheet behaviour. Radar allows us to do all of these things. This paper explains how, and presents some of the important results in this field.

Antarctica

Antarctica is dominated by its great ice sheets, whose effect can be felt thousands of miles away (figure 1). They hold 90% of the world's ice and 70% of its fresh water, locked into slow-motion conveyors that creep downhill from the polar plateaus. New snow swept by storms into the cold, dry interior continuously feeds the conveyors as the snowflakes drift, settle, are buried and finally become compressed into layers of ice. The pressure produced by the accumulation of ice over thousands of years deforms the normally brittle ice, like a metal near its melting point. Ice crystals glide along planes of weakness or repeatedly recrystallize at grain boundaries. Pressure and sheer stress are higher at greater depth, and temperatures are also higher through geothermal heating and the insulating effect of the overlying ice. The result is faster creep, leading to faster flow of the ice sheet towards the sea.

The fastest creep occurs where the ice is thickest and the surface steepest, and flow converges as it moves downhill. When enough ice is flowing together, an important change takes place. The ice at the bottom reaches its pressure melting point, a little below 0 °C, and releases liquid water along the ice sheet bed. Bare rock becomes slippery, mud softens and the great body of ice above is able to slide rapidly over the ground below. Flow rates increase from metres a year up to metres per day, and the converging flow forms a glacier flowing down a bedrock trough, or an ice stream—a thick river of ice within the ice sheet—which is eased along by further frictional melt at its bed. Glacier and ice stream behaviour is vital to the health of the Antarctic ice sheets. Ice streams drain 80% of all the throughput of this cryological cycle so that, when their discharge is in balance with the rate of falling snow, the ice sheet's volume is maintained. Greater or less snowfall, if sustained, will slowly thicken or thin the ice sheet, leading to a change in the driving stress acting on the ice streams and, over thousands of years, they will slow down or speed up to regain equilibrium.

Over the last few years, more detailed studies have shown that the ice streams and glaciers, and hence the ice sheets themselves, can be highly sensitive to external stimuli and to positive feedback within the system. Water—pooling and flowing under the ice; streaming off melting glaciers; ebbing and flowing as ocean tides that buoy up the margins; and upwelling as warm ocean currents in coastal waters—is the key to the sensitivity of the Antarctic ice sheets. The change in global sea level, now rising at 3 mm per year, is our prime motivation for studying Antarctic glaciology.

 0031-9120/07/050442+15$30.00

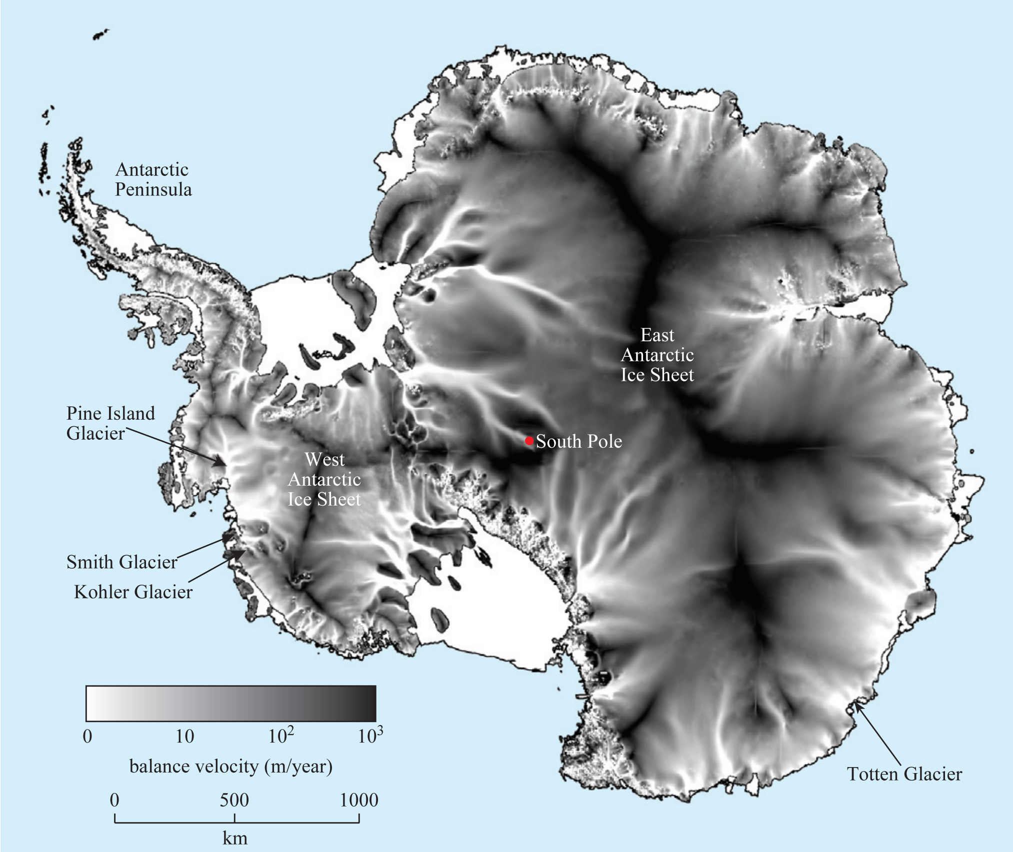


Figure 1. Antarctica, showing the classical division of the ice sheet into the West and East Antarctic Ice Sheets and the Antarctic Peninsula. The surface shading is scaled to the 'balance velocity', the ice flow speed assuming the ice sheet is in balance with the current climate (after [1]).

How to study Antarctica

The history of Antarctic glaciology is a story of scale. Early research was done by small field parties with dog-sled teams and tents who faced 14 million square kilometres of uncharted territory. Surface topography was laboriously surveyed through triangulation by theodolite (figure 2). Snow accumulation was measured by digging small pits by hand and counting the layers. Each measurement of glacier flow was hard won over short summers by watching the movement of a few stakes knocked into the snow. Ice depths were obtained by setting off explosive charges at the surface and measuring the shock waves echoing off the bed. In the 1950s, however, new developments in physics, and in particular radar, revolutionized the scale and scope of Antarctic research.

Radar glaciology

Radar (radio detection and ranging) technology consists of a radio transmitter capable of sending out electromagnetic pulses across selected frequencies ranging from 1 MHz to 300 GHz, and a receiver able to detect and record the time delay and amplitude of the radar waves scattered back towards the transmitter off any reflecting surface (figure 3a). Radar waves have physical properties that make them especially valuable to studies of ice sheets: at low frequencies, they travel almost as freely through ice as they do through air. As the frequency is increased, the wavelength becomes closer in scale to layers within the ice and then to snow crystals and layers near the surface, and these features come to dominate the reflection mechanism. Radar reflections are particularly sensitive to

Figure 2. Early field survey work by the British Antarctic Survey—pioneering but slow and difficult.

contrasts in the electrical properties of the material that the waves encounter. At the typical low frequency of radar waves transmitted down into the Antarctic ice sheet, some of the energy is reflected back to the receiver off the ice surface and the rest is transmitted onwards to reflect from internal layers within the ice that represent long-buried individual snowfall events, and then ultimately from the ice/bed boundary (figure 3b).

Radar systems used to investigate the Antarctic ice sheet are operated from three different types of platform: ground-based (i.e. over-snow), airborne, and spaceborne (figure 3a). Of these, the first two are used to mount ice-penetrating radars that can ‘see’ well down into the ice-sheet interior and often all the way down to the bed. Ground-based systems typically consist of the radar mounted on a sled towed by a snow vehicle such as a skidoo (figure 3c), and they afford the user the greatest degree of control and accuracy; however, they are restricted in the area of the ice sheet that can be covered in a single survey. Airborne systems (figure 3d) provide a more feasible means of surveying larger areas (up to thousands of km^2) but are expensive to mount, especially in the interior of the ice sheet away from the scientific bases scattered around the Antarctic coast.

Satellite-mounted radar systems can sweep over the whole continent in just a few weeks. The onboard radars do not need sunlight and can see straight through clouds, so the long night of polar winter and the stormy weather around the coasts are no hindrance to continual surveying. To date, however, the long antennae and high-powered transmitter needed to make ice-penetrating radar waves from space have not been feasible. Nevertheless, two types of satellite radar system have proved invaluable to scientists over the last two decades: *altimetric* radar and *imaging* radar, both of which employ super- and ultrahigh frequencies that can ‘see’ straight through the atmosphere to the ice sheet surface.

Very much like ice-penetrating radar, the altimetric radar satellites ping the surface with a series of pulses that illuminate a round footprint on the ground, and with some detailed measurements of the satellite orbit, the time delay of the echo gives the ice sheet height.

Imaging radar is even more sophisticated. As the satellite flies by, three things are measured: the time delay, amplitude and the phase of the reflected radar signal. Because the satellite is moving (fast!), the reflections from the leading edge of the footprint are Doppler-shifted to a shorter wavelength, and those from the trailing edge to a longer wavelength. By using the phase shifts of all of the echoes returning from the surface, their distance along the footprint can be calculated. Pointing the radar off to one side allows it to illuminate a whole swath of surface where the echoes from the farthest edge take longest to return, while those from the nearest edge take the shortest time. Combining all this information on the Doppler shift along the satellite’s path and the time delay across it, the strength of reflection for individual points in the swath can be measured—instead of seeing one big footprint, the radar can see lots of small ones as if the satellite actually had a very long radar antenna (or aperture), this is a technique known as ‘synthetic aperture’ radar (SAR). All of these little footprints are built up into a full and detailed image, almost like a photograph of the surface that shows the strength of reflection and the location of mountains, sea, glaciers, crevasses and subtle variations in the type of snow (figure 4).

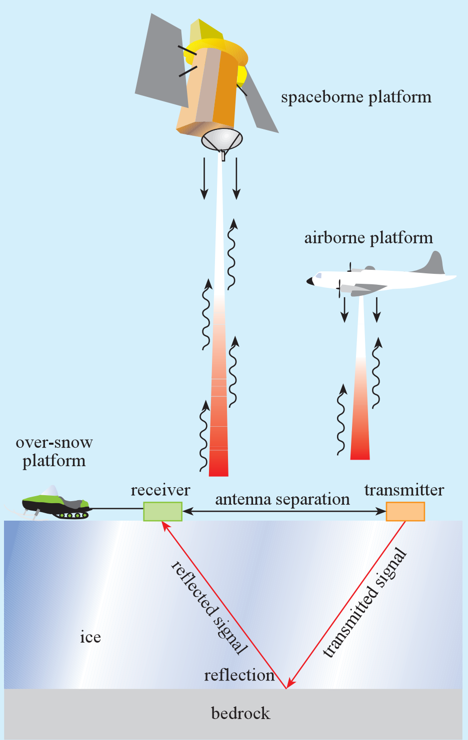


Figure 3a. A conceptual diagram outlining the basic principles of ice radar and the various platforms on which radar systems are mounted.

Figure 3c. Field deployment of over-snow radar towed by a skidoo.

Figure 3d. Airborne radar antennae mounted on the wings of a Twin Otter aeroplane (copyright David Leatherdale).

Using radar for real-world problems

So far we have seen how important Antarctica is as a major part of the world's hydrological (or cryological) cycle, and how we can use radar as a geophysical tool to look both at the surface and inside the ice, but how is it being used to help

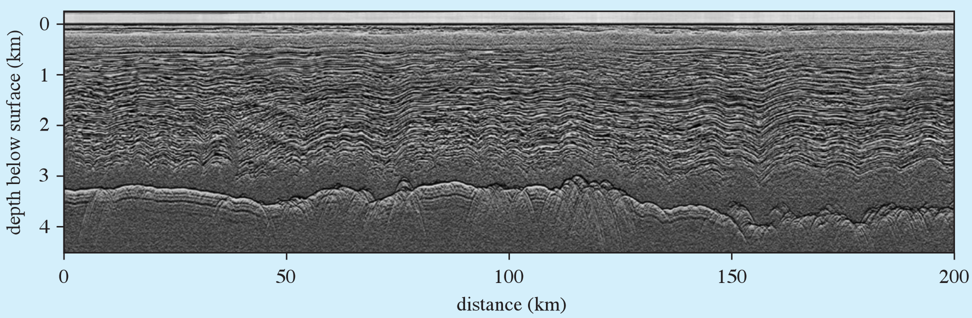


Figure 3b. An example of a radargram, an image showing the strength of radar echoes from the surface, internal layers and bed of a section of ice sheet.

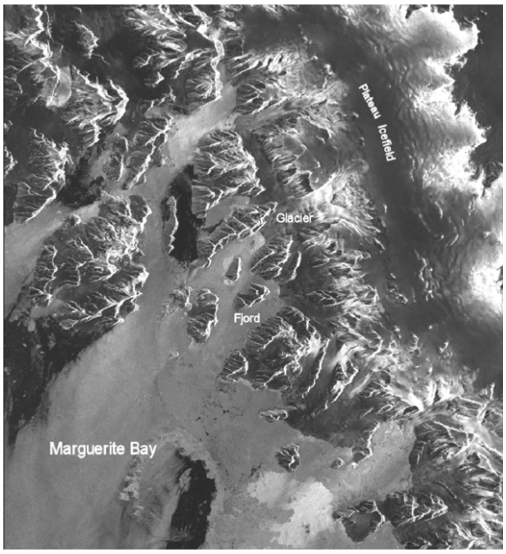


Figure 4. Synthetic aperture radar (SAR) image of a 100 km wide section of the Antarctic Peninsula coast. This shows the main spine of the peninsula to the northeast with glaciers flowing down into fjords to meet the sea. The snow high on the plateau appears quite dark compared to the surface of the glaciers where they flow steeply down off the plateau, fracturing into crevasses that make a rough surface with a relatively high dielectric contrast with the air. Over the sea, the smooth areas of calm water appear black, while choppy seas and floating sea ice appear brighter. The mountains appear to lean over, the result of the satellite seeing them from one side.

answer the important questions, like how much ice is there in Antarctica? How has it changed in the past? Is it changing now? What will happen to the ice sheets and glaciers in the future? In this section we look at four case studies of active research on the ground, in the air and from space, all using radar and all aimed at answering these questions.

Taking stock of Antarctica

Just how much ice is there and what is its history? We take a look with ice-penetrating radar.

Question 1: How much ice is there? We now know that were all the ice in Antarctica to melt, the global sea level would rise by nearly 65 m. This is a frightening thought, given that 70% of the world's population lives on coastal plains, with 100 million people living within one metre of the current sea level. How did scientists arrive at this figure, and how can we predict how quickly the melting of this ice might contribute to rising sea levels?

Case study: airborne radar—calculating past and present volumes of Antarctic ice. Prior to the 1960s we really had very little idea how much ice existed in Antarctica and therefore on the Earth as a whole. Before the invention of radar, the sparse measurements of ice depths obtained from scattered seismic surveys were insufficient to draw up a comprehensive picture of ice depths across Antarctica. From the 1960s onwards what really transformed our knowledge of the continental ice volume was the incorporation of radar systems into aircraft, and their implementation to survey large swaths of the Antarctic ice sheet. Between 1967 and 1979 an international consortium mounted a systematic survey of Antarctica, crisscrossing ∼50% of the continental ice sheet at a grid spacing of 50–100 km (figure 5a). These surveys showed that the ice was on average 2.5 km thick and reached a maximum depth of 4.7 km [2].

After 1979, these wide-ranging surveys were discontinued, but further medium-range surveys carried out by several international teams have continued to fill in the remaining gaps. In 2001, over two million of these thickness measurements were brought together by the British Antarctic survey into BEDMAP, a comprehensive map of the subglacial topography shrouded beneath the Antarctic ice sheet (figure 5b). BEDMAP revealed for the first time a landscape hidden for over a million years and showed that the Antarctic ice sheets now hold 25.7 million km^3 of ice [3]. Close examination of the radar echoes from the bed has, in addition, revealed at least 150 subglacial lakes, with potentially exotic ecosystems that may soon be explored [4].

These airborne radar surveys over Antarctica also revealed internal layers visible between the bed and surface radar echoes (figures 5c and 5d). These layers show differences in ice density, acidity or the arrangement of ice crystals (its 'fabric') at the time the layer was deposited, and so act as isochrones (layers of equal age). Because their stratigraphy results from a combination of their rate of burial by snow and the internal flow field of the ice [5], internal layers are used to validate complex numerical models that aim to replicate ice flow through Antarctica. These models are used by scientists to investigate how

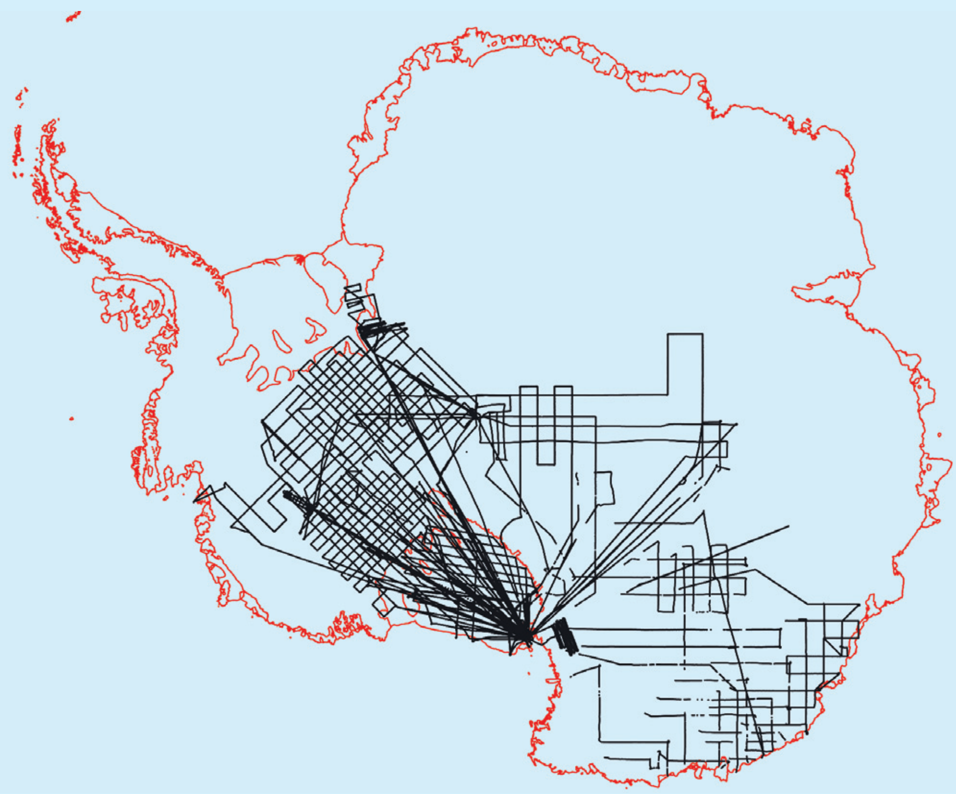


Figure 5a. Airborne radar flight tracks over Antarctica surveyed by Scott Polar Research Institute/National Science Foundation/Technical University of Denmark 1967 to 1979.

quickly the ice sheet has responded to past climate changes and, by extrapolation, how quickly it might respond to future climatic stimuli such as global warming. Airborne radar currently provides the only means to image these vital internal layers (and therefore internal flow fields) over the continental-scale distances appropriate for modelling the evolution of the Antarctic ice sheet.

Question 2: How have the ice sheets behaved in the past? The big ice sheets and the many smaller ice caps, ice streams and glaciers are never entirely in balance with their environment—they are forever expanding and contracting, shifting, slowing down or speeding up on different temporal and spatial scales. At the moment, many are still adjusting to the end of the last ice age 10 000 years ago as well as warmer and cooler, wetter and drier spells up to the present day. Measuring the sensitivity of the cryosphere to change is essential so that our numerical models can predict its future. To do this we need a record of past changes in both climate and ice extent in Antarctica. Past climates can be reconstructed from a variety of records, such as the bubbles of air trapped through time in ice cores. But how can we know what shape and size the ice caps and ice sheets were in the past? We wanted to find out how the size of ice caps on the Antarctic Peninsula have been changing, but very few measurements exist and none go back more than 60 years.

Case study: radar on a sledge—bumps, double bumps and ice cap history. Radar can help us to reconstruct the position and thickness of ice divides (ridge crests) that define the geometry of an ice cap. This is possible because of the

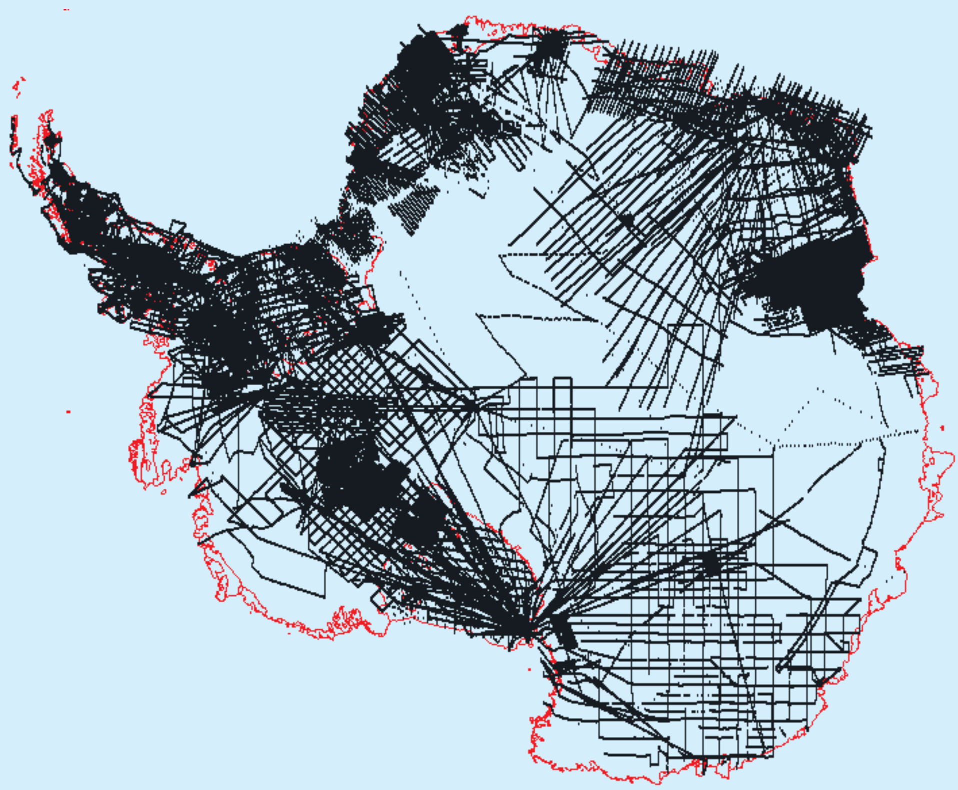


Figure 5b. Coverage of ice thickness measurements obtained by airborne and over-snow radar (and some seismic measurements) used in 2001 to produce BEDMAP, a map of subglacial topography beneath the Antarctic Ice Sheet.

way that ice divides leave a fingerprint in the ice layers buried below. The rate of creep-flow of ice is very sensitive to the surface slope of the ice cap. When the ice starts to creep downhill, the crystals become oriented in the direction of flow because this configuration (fabric) offers the least resistance. At an ice divide, the surface is flat and the ice does not move, so its fabric does not evolve—the ice here remains stiffer than the ice on either side of the divide. Over time, the isochrone layers within the ice are drawn down by the downhill flow, except in the stiffer divide-ice. When we take a radar profile across a present (or past) ice divide, we can see a bump in the layers (figure 6a) that shows where the ice is stiff, and we can see if the divide has migrated. In addition, we can use models of creep dynamics with measurements of the bump amplitude with depth to work out when a divide started to thin, and how quickly it has been happening.

Over the Antarctic summer 2006/2007, we went bump-hunting on Adelaide Island, Antarctic Peninsula, with a radar system towed over the snow by a skidoo. We sent down radar pulses into the ice as we drove and recorded the reflections. As the ice cap is only a few hundred metres thick, we could use high-frequency waves without worrying that all of the energy would be absorbed or scattered away into the depths, and these short wavelengths were very good for picking out the fine detail of layers within the ice. We came back with a set of bumps that we measured, and then fed the measurements into a computer model built using the physics of ice (figure 6b). This told us that the ice cap on Adelaide Island has been thinning strongly over the span of a few centuries.

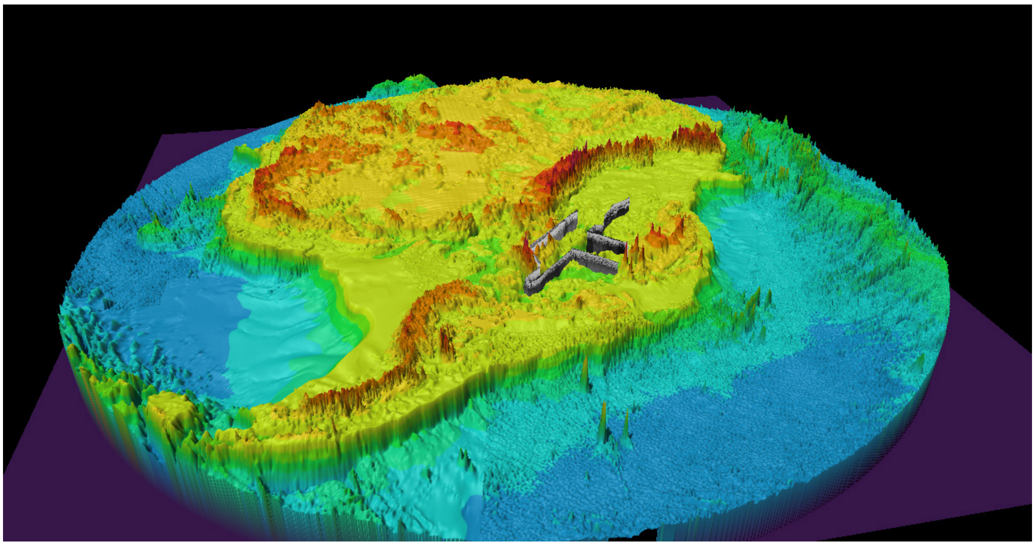


Figure 5c. A three-dimensional visualization of an airborne-radar-derived radargram containing surface, internal and bed echoes emplaced over 60× exaggerated subglacial topography from BEDMAP.

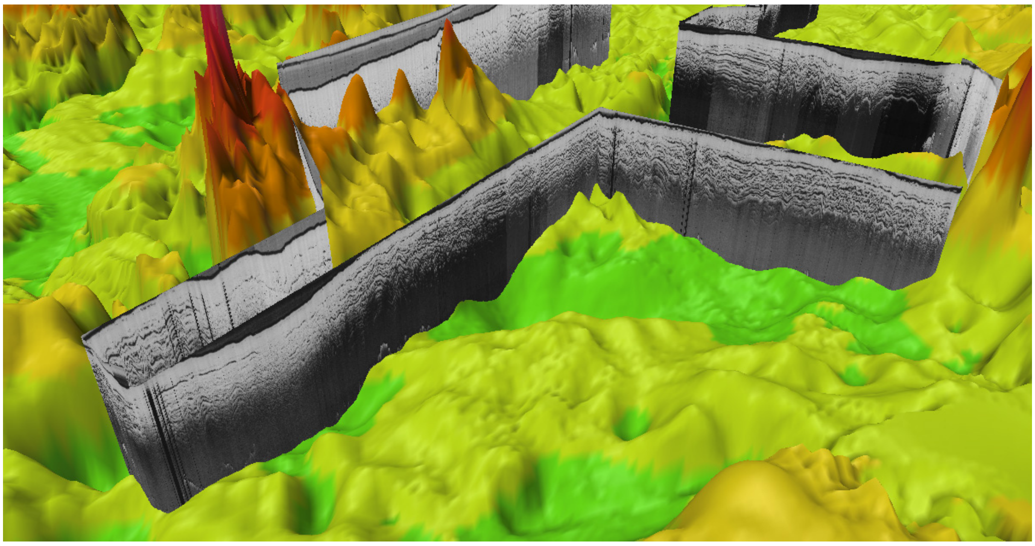


Figure 5d. Close-up of (c).

This finding supports the theory that the Antarctic Peninsula is still responding to the end of the last ice age when the ice was much thicker and more extensive, and it gives us some numbers to use in calibrating numerical models of this long-term deglaciation.

Shocks to the system

Watching from space as the 'sleeping giant' awakes.

Question 3: What about the present? Are glaciers changing right now? The Antarctic Peninsula (figure 1) is a narrow, jagged mountain chain with a polar maritime climate, drained by fast-flowing glaciers. All along the coast these glaciers reach the sea to break off as icebergs or, in places, merge into floating ice shelves. This region makes up only 1% of the Antarctic continent but it receives 10% of its snowfall and it is the only area that

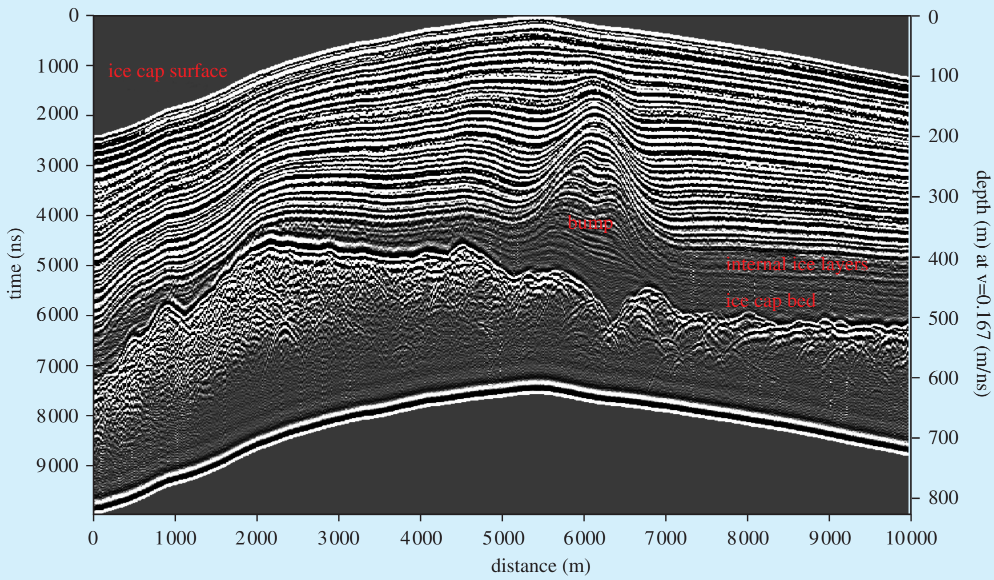


Figure 6a. A radargram along a 10 km profile that spans the drainage divide of the ice cap on Adelaide Island, Antarctica. Many internal layers are visible in the ice of this 400 to 500 m thick ice cap, and prominent near the centre is the bump of stiff ice that allows us to recreate the ice cap history. The bump originally formed right below the ice divide (the ridge crest) but now the divide has migrated about 1 km to the west (left), as the ice cap evolves with its changing environment.

experiences substantial summer melting. Glaciers in this area are being affected by ocean waters that have warmed by more than 1 °C and a regional climate that has warmed by nearly 3 °C since the 1950s, intensifying summer melting [6–8]. What effect is this melting having on the flow of glaciers on the Antarctic Peninsula, and what can it tell us about the future of the main Antarctic ice sheets if they get warmer too?

After years of melt-driven thinning, the floating Larsen A ice shelf near the northern tip of the peninsula finally rotted into a dramatic collapse in the unusually warm summer of 1995. Seven years later, neighbouring Larsen B, 11 500 km^2 or 500 million billion tons of ice shelf, also collapsed in a few weeks, weakened by thinning and one of the warmest summers on record [9]. These collapses, watched over by the ERS and Envisat imaging radar satellites, occurred when enough snow had melted to flood crevasses in the ice shelf surface. The water in these cracks, slightly more dense than the surrounding ice, seems to have driven down through the shelf like a wedge, unable to stop until the cracks broke through the bottom of the floating ice, leaving them fractured and weak [10]. Larsen B had existed for at least 110 000 years, since before the last Ice Age, so this collapse shows that the regional climate has become exceptional [11].

After the collapses, radar images from the same satellites were used to measure the flow rate of the grounded glaciers that previously fed the shelves. They showed that the glaciers accelerated by up to eight times, causing rapid thinning as ice stored on land was discharged to the sea [12, 13]. The volume of ice involved and consequent sea level rise was small, but this is seen as an important analogue for the much larger ice-stream–ice-shelf systems of the East and West Antarctic ice sheets, through which 80% of Antarctic ice drains. It is now clear that intact shelves restrict the flow of their tributary glaciers. Their loss allows the glaciers to accelerate and thin, a process that could threaten the stability of the much greater body of ice in the West Antarctic ice sheet with its giant Ross and Ronne ice shelves.

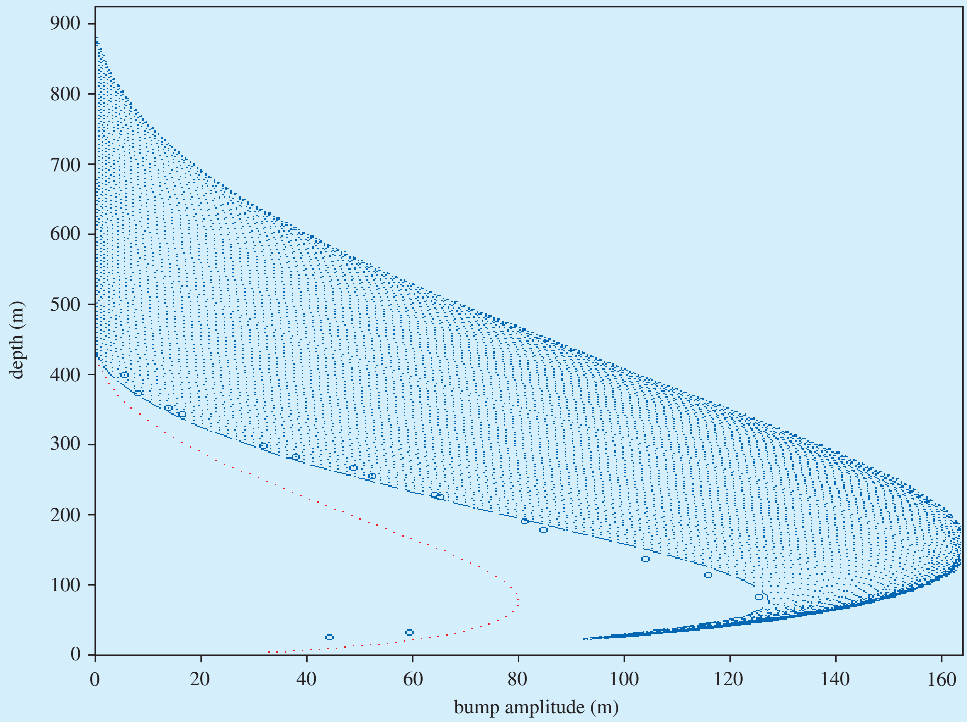


Figure 6b. Fitting a model of ice cap thinning history (blue dashed lines) to the shape of the measured bump (blue circles).

Case study: radar in space—quickening glacier flow on the Antarctic Peninsula. Only some of the Antarctic Peninsula's glaciers flow into ice shelves. We wanted to know whether the many glaciers that flow straight into the sea (see, e.g., figure 4) are also changing. We found high-resolution radar images from 1993 to the present and we used 75 images to track the movement of crevasses in the glacier surfaces over time, enabling us to measure changes in the glacier flow rates on a regional scale [14].

When we compared our measurements made between 1993 and 2003, we found that the average flow rate of glaciers on the west coast of the peninsula had increased by 12%. The pattern is similar all along the coast, with the majority (60%) of glaciers accelerating by more than 5% (figures 7a–7c). At first we thought that this was caused by melting snow percolating down and lubricating the glacier beds, so we looked for a sign of the flow rates rising as spring arrived, but found none. We looked to see if warm summers tied in with summers of fast flow, but again found no link. We could not account for the speed-up either through variations in summer weather or the result of measuring the flow in different stages of the melt season [14].

Then we looked again at the other evidence: 87% of these glacier fronts were in retreat [15]. When we looked at old photos of research stations dotted along the coast, we could see that the banks of snow and ice near these huts have been thinning over the decades, and we know more snow is melting away each summer [16]. We began to suspect a link between thinning of the glaciers over several decades, frontal retreat and the acceleration that we had measured. This fits very well with a recent theory: when the terminus of a glacier ending in the sea starts to thin, it begins to float off its bed. This allows it to slide faster, which in turn feeds back into further thinning. As the margin goes afloat, more and more icebergs break

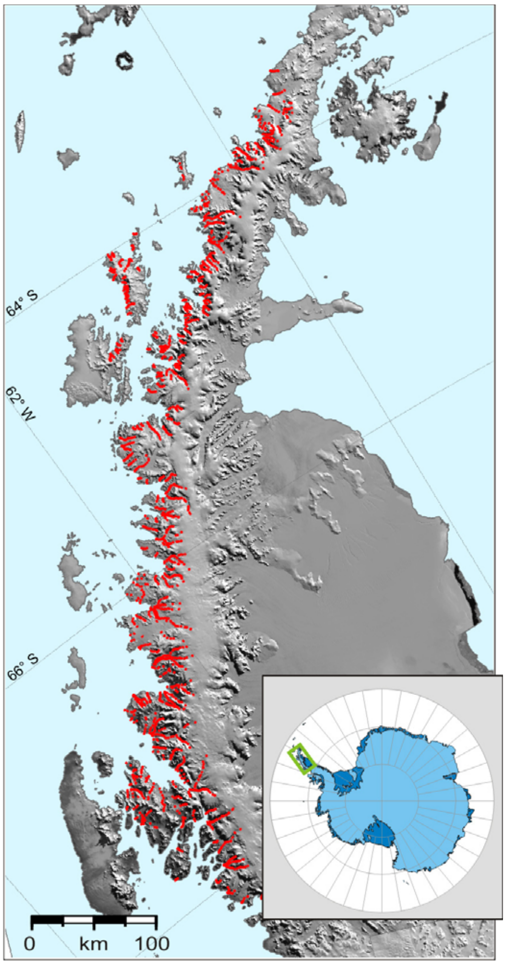


Figure 7a. The 400 plus glaciers (in red) on the west coast of the Antarctic Peninsula whose flow rates we measured by tracking features in radar (SAR) images [14].

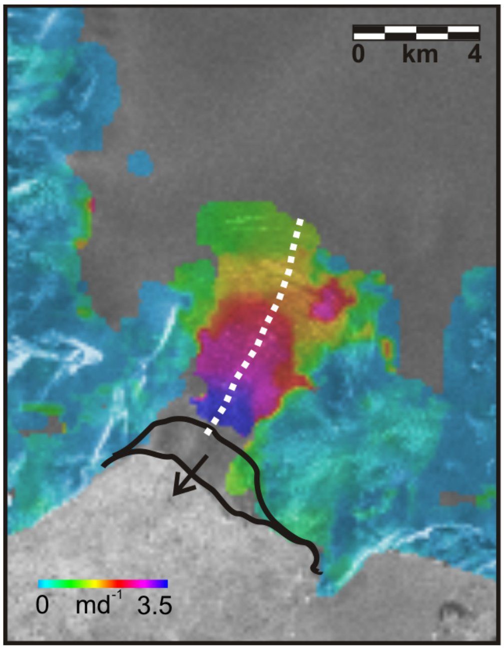


Figure 7b. An example of a glacier on the Antarctic Peninsula accelerating. The colours represent the flow rate in 2003, the black arrow the flow direction, the black dashed lines show how the front has retreated, and the white line shows the location of the profiles in figure 7c [14].

off and the glacier front retreats [17]. Given the regional scale of the response, it seems likely that the thinning was triggered by the observed warming and increase in summer melt observed on the Antarctic Peninsula since the 1950s.

Faster flow of the glaciers means that ice is lost from the land to the sea. When we added up the sea level contribution from the glaciers in our study, the Larsen A and B tributary glaciers and the contribution from melt, we came to a total of 0.16 ± 0.06 mm a^{-1}, which is approximately the same as that coming from melting Alaskan glaciers. Furthermore, we can compare it with the best estimates for the rest of Antarctica combined, which range from 0.08 ± 0.03 mm a^{-1} to -0.08 ± 0.08 mm a^{-1}. The sea level contribution identified in our study is large enough to show that the total Antarctic sea level contribution is positive [14]. More importantly, it shows that glaciers do not just melt slowly away when the climate warms: many of them also speed up, a much quicker way of depositing ice into the sea.

Question 4: Are we seeing the start of something big? We know that Antarctica keeps changing, locally and on a continental scale, slowly and quickly. We cannot just look at one part just for one moment and expect to understand it: clearly, what we need is a way of monitoring the whole ice sheet over a long period. In particular, we need to measure changes in the volume of stored ice and in the flow of glaciers and ice streams.

Case study: radar in space—the steady east, the wild west. Radar altimetry satellites that bounce

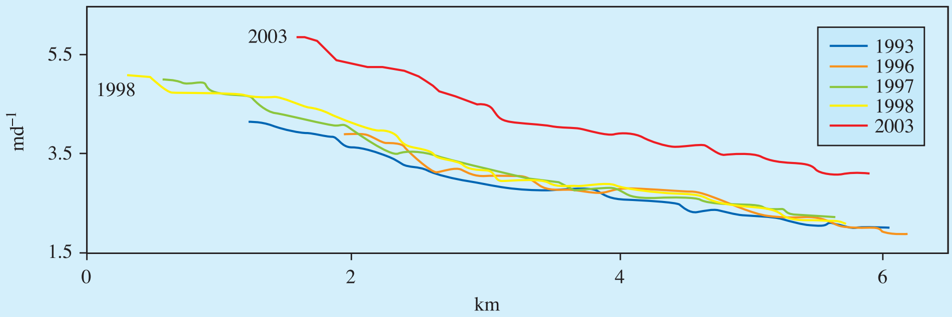


Figure 7c. The graph shows the way that the glacier flow increased dramatically between 1998 and 2003 after a period of more gradual acceleration [14].

radar pulses off the surface to measure the height of the ice sheet rapidly completed the topographic map begun by the airborne and field surveys, mapping most of the continent in the space of months with high vertical precision. What is really useful is that they keep going, mapping and remapping the height of the ice. As time passes, the more rapid changes in height start to emerge, and then the more subtle ones. Eventually, a picture of ongoing ice sheet evolution develops.

It has emerged that over the last few years some parts of the ice sheet are thinning quickly, at tens of centimetres per year, particularly some fast-flowing ice streams near the coast of West Antarctica, while most of the higher parts of the ice sheet are unchanged or are thickening slightly [18] (figure 8(a)). The slight thickening can be explained by spells of heavier snowfall, which can vary considerably year to year, but the rapid thinning near the coast is too great to be explained by less snowfall or by melting.

Could these large ice streams be speeding up and losing ice like the glaciers on the Antarctic Peninsula? This is where the final and most spectacular radar technique, interferometry, comes in. This technique can give remarkably precise measurements of surface movement over very large areas. As we described earlier, images can be made up from satellite radar pulses because the phase of the returning radar waves is recorded, and so the Doppler shift can be used to locate the source of the reflection (the SAR technique). This phase information can also be used in another way. By taking two images of an ice stream separated by a day or so, all the measurements of phase made for every location in the image can be compared. By taking into account the change in position of the satellite, differences in phase between the two images result from changes in the distance from the satellite to the surface. The phase of the returning waves can be measured to a fraction of a wavelength, so assuming the typical imaging radar wavelength of about 5 cm, movement of the surface can be measured to millimetre precision (figure 8(b)).

Interferometric (phase differencing) measurements of flow have now been made for nearly all of the Antarctic ice streams and major outlet glaciers for several different dates, and they confirm that those that are thinning strongly have also been accelerating strongly [19]. In particular, Pine Island Glacier in West Antarctica was found to have accelerated by over a third in 30 years. Its neighbour Smith Glacier accelerated by 85% in 15 years, and Kohler Glacier is now four times faster than the speed needed to keep it in balance [19]. Pine Island Glacier is the biggest in West Antarctica, draining 10% of its ice, and it holds the equivalent of 0.5 m of sea level rise. The biggest equivalent glacier in East Antarctica, Totten, is also accelerating. These areas are too cold to have much surface melting but instead, it seems that warm ocean currents are shifting and now reach the floating glacier fronts, melting them from below [20]. All of the major Antarctic glaciers and ice streams end in the sea and so are prone to the same thinning–acceleration–thinning positive feedback described for the Antarctic Peninsula glaciers. It is likely that

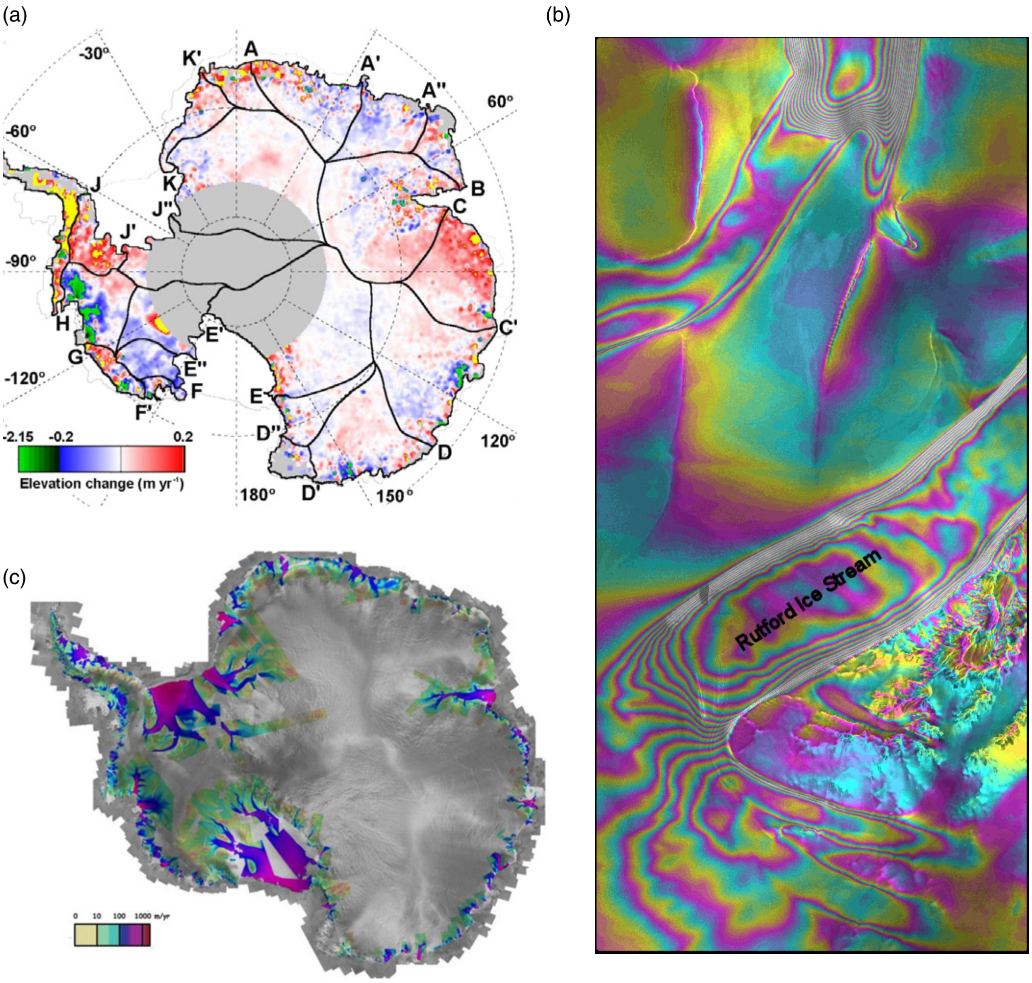


Figure 8. (a) The rate of change in surface height for the whole continent between 1992 and 2003 is shown in this map, produced using 120 million echoes from altimetric radar satellites (redrawn from [18]). Strong thinning in West Antarctica is apparent in shades of green. (b) This interferogram shows the phase difference between two satellite SAR images acquired one day apart over the Rutford Ice Stream area of West Antarctica, cycling red-yellow-blue for each full wavelength. The scene is 100 km wide. The band of closely spaced 'fringes' either side of the ice stream are the shear margins, with a strong velocity gradient from zero to 1 m per day on the ice stream. (c) This map shows the flow rate (in colour) of all of the major Antarctic glaciers and ice streams, measured by SAR interferometry [19]. Nearly all of the snow falling on Antarctica passes through these outlets and so knowing their flow rates is vital to understanding the state of balance of the continent's ice.

such glacier dynamic effects will dominate the sea level rise over the next centuries.

The best estimate (of the Intergovernmental Panel on Climate Change in 2007) [21] is that the sea level is likely to rise by 28–43 cm over the next century—but the accelerating glaciers and ice streams described here mean that this estimate is probably too low.

Summary

The great Antarctic cryological cycle is a key part of the global cycle of water. It controls the sea level around the world and so it is important that we learn to predict how the ice sheets and glaciers will change in the future. To do this, we need to know how they have changed in the past and how they are changing now, but the vast scale and inaccessibility of the continent make this a difficult task. Radar is a geophysical tool uniquely suited to this glaciological challenge. We can use it to look through the ice to see the bed and layers deposited as snow thousands of years ago, or to look down from space to make images of the surface, to measure its height and see how it is moving. What radar has shown us is a picture of change, from the thinning ice caps and accelerating glaciers of the Antarctic Peninsula to the heavier snows high on the polar plateaus, and the ominously lurching Pine Island Glacier and its neighbours in West Antarctica.

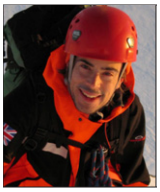
Although we now have a wealth of information on Antarctica, we have also found greater complexity than we expected, and a few surprises. We are not yet able to predict the future of the ice sheets with confidence because we still do not have sufficient understanding of what happens at the bed of ice streams to control their flow, but we are getting closer, and the insights that radar gives us will be key to solving the puzzle.

Received 3 July 2007
doi:10.1088/0031-9120/42/5/001

References

[1] Le Brocq A M, Payne A J and Siegert M J 2006 West Antarctic balance calculations: Impact of flux-routing algorithm, smoothing algorithm and topography *Comput. Geosci.* **32** (10) 1780–95
[2] Drewry D 1983 *Antarctica: Glaciological and Geophysical Portfolio* (Scott Polar Research Institute: University of Cambridge)
[3] Lythe M and Vaughan D G 2001 BEDMAP Consortium. BEDMAP: a new ice thickness and subglacial topographic model of Antarctica *J. Geophys. Res.* **106** (B6) 11335–52
[4] Siegert M J, Carter S, Tabacco I, Popov S and Blankenship D D 2005 A revised inventory of Antarctic subglacial lakes *Ant. Sci.* **17** 7
[5] Miners W D, Wolff E W, Moore J C, Jacobel R and Hempel L 2002 Modeling the radio echo reflections inside the ice sheet at Summit, Greenland *J. Geophys. Res.* **107** (B8) doi:10.1029/2001JB000535
[6] Meredith M P and King J C 2005 Rapid climate change in the ocean west of the Antarctic Peninsula during the second half of the 20th century *Geophys. Res. Lett.* **7** 32
[7] Smith R C and Stammerjohn S E 2001 Variations of surface air temperature and sea-ice extent in the western Antarctic Peninsula region *Ann. Glaciol.* **33** 493–500
[8] Harangozo S A 2006 Atmospheric circulation impacts on winter maximum sea ice extent in the west Antarctic Peninsula region (1979–2001) *Geophys. Res. Lett.* **33** L02502
[9] Van den Broeke M 2005 Strong melting preceded collapse of Antarctic ice shelf *Geophys. Res. Lett.* **32** L12815
[10] Scambos T, Hulbe C and Fahnestock M 2003 Climate-induced ice shelf disintegration in Antarctica *Antarctic Peninsula Climate Variability: Historical and Paleonenvironmental Perspectives* (*Ant Res Series* vol 79) ed E Domack, A Leventer, A Burnett, R Bindshadler, P Convey and M Kirby pp 79–92
[11] Domack E *et al* 2005 Stability of the Larsen B ice shelf on the Antarctic Peninsula during the Holocene epoch *Nature* **436** 681–5
[12] Scambos T A, Bohlander J A, Shuman C A and Skvarca P 2004 Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment Antarctica *Geophys. Res. Lett.* **22** 31 L18402
[13] Rignot E, Casassa G, Gogineni P, Krabill W, Rivera A and Thomas R 2004 Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf *Geophys. Res. Lett.* **31** L18401 doi:10.1029/2004GL020679
[14] Pritchard H D and Vaughan D G 2007 Widespread acceleration of tidewater glaciers on the Antarctic Peninsula *J. Geophys. Res. Earth Surf.* **112** F03S29
[15] Cook A, Fox A J, Vaughan D G and Ferrigno J G 2005 Retreating glacier-fronts on the Antarctic Peninsula over the last 50 years *Science* **22** 541–4
[16] Smith A M, Vaughan D G, Doake C S M and Johnson A C 1998 Surface lowering of the ice ramp at Rothera Point, Antarctic Peninsula, in response to regional climate change *Ann. Glaciol.* **27** 113–8
[17] Vieli A, Funk M and Blatter H 2001 Flow dynamics of tidewater glaciers: a numerical modelling approach *J. Glaciol.* **47** 595–606
[18] Wingham D, Shepherd A, Muir A and Marshall G J 2006 Mass balance of the Antarctic ice sheet *Phil. Trans. R. Soc.* **364** doi:10.1098/rsta.2006.1792
[19] Rignot E 2006 Changes in ice dynamics and mass balance of the Antarctic ice sheet *Phil. Trans. R. Soc.* A **364** 1637–55
[20] Shepherd A, Wingham D J and Rignot E 2004 Warm ocean is eroding West Antarctic ice sheet *Geophys. Res. Lett.* **31** L23402 doi:10.1029/2004GL021106

[21] IPCC 2007 *Working group II report: Climate Change 2007 'Impacts, Adaptation and Vulnerability'* (Geneva: IPCC)
[22] Bamber J L, Vaughan D G and Joughin I 2000 Widespread complex flow in the interior of the Antarctic ice sheet *Science* **287** 1248–50



Hamish Pritchard is a glaciologist with the British Antarctic Survey. He specialises in using satellite radar remote sensing and applied geophysics to study glacier and ice-stream dynamics and ice cap history, with field sites on the West Antarctic Ice Sheet and the Antarctic Peninsula. He gained his PhD in glaciology from the University of Leeds.

Robert Bingham is a radar geophysicist with the British Antarctic Survey, and deploys both airborne and oversnow radar systems over the Antarctic Ice Sheet to measure the subsurface properties of ice. He gained his PhD in glaciology from the University of Glasgow, and thereafter trained as a specialist in cryospheric radar systems at the UK Natural Environment Research Council's Centre for Polar Observation and Modelling (NERC-CPOM), Bristol Glaciology Centre. His wider research interests encompass polar glaciology, investigations of englacial and subglacial environments, and glacier and ice-sheet dynamics and hydrology.