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The environment and evolution of the West Antarctic ice sheet: setting the stage

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The West Antarctic ice sheet is the last ice sheet of the type cradled in a warm, marine geologic basin. Its perimeter stretches into the surrounding seas allowing warmer ocean waters to reach the undersides of its floating ice shelves and its relatively low surface elevation permits snow-carrying storms to extend well into its interior. This special environment has given rise to theories of impending collapse and for the past quarter-century has challenged researchers who seek a quantitative prediction of its future behaviour and the corresponding effect on sea level. Observations confirm changes on a variety of time scales from the quaternary to less than a minute. The dynamics of the ice sheet involve the complex interaction of ice that is warm at its base and cold along the margins of ice streams; subglacial till that is composed of a combination of marine sediment and eroded sedimentary rocks; and water that moves primarily between the ice and bed, but whose flow direction can differ from the direction of ice motion. The pressure of the water system is often sufficient to float the ice sheet locally and small changes in the amount of water in the till can cause it to rapidly switch from very weak to very stiff.

Keywords: West Antarctica; ice sheet; glaciology; ice sheet dynamics

1. Introduction

The West Antarctic ice sheet is capable of rapid change and is large enough to raise sea level 6 m globally. Intensive scientific study has focused on this ice sheet to assess the likelihood of such calamitous change and the time scale over which any changes could be expected (Alley & Bindschadler 2001). A wide range of disciplinary experts has been engaged in this study because, as shall be described in this paper, the ice sheet's environment and the influence of changes in this environment are inextricably connected to its current and future behaviour.

This paper discusses the general geography and environmental setting of the West Antarctic ice sheet as well as some fundamental aspects of its dynamics as preparation for the series of papers that follow. The ice sheet's environment is responsible for its replenishment, through snowfall, as well as its losses, through melting and calving into the surrounding seas. In between, the ice sheet

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transports its mass from its interior regions to its perimeter by means of fast moving ice streams and outlet glaciers. The critical characteristics and even location of these ice streams are dependent upon the underlying material, how it came to be deposited prior to the mantling of the present-day ice sheet and how water at the subglacial interface flows and interacts with the subglacial material.

Sustained research for the past quarter century has revealed a host of changes, both inferred and directly measured. This suite of variation is summarized to give the reader an appreciation for the complexity of ice sheet behaviour as well as a framework into which more detailed discussions of various processes can be fit. Such a framework of time scale enables a better linking of those processes relevant to the behaviour on any particular time scale.

2. Geography

West Antarctica refers to that portion of Antarctica that lies predominantly in the western hemisphere. The Transantarctic Mountains provide an imperfect, but convenient, division between the East and West Hemispheres and thus are usually taken as the boundary between the West Antarctic ice sheet and the East Antarctic ice sheet (figure 1). Numerous glaciers drain a portion of the East Antarctic ice sheet through this 3500 km-long mountain chain into the Ross and Filchner Ice Shelves. The area of West Antarctica is approximately $1.97\times 10^6\ \mathrm{km}^2$ and is 97% ice covered while East Antarctica covers $10.35\times 10^6\ \mathrm{km}^2$ and is 98% ice covered (Drewry *et al.* 1982).

The Antarctic Peninsula adds another $522\,000\ \mathrm{km}^2$ of area to the continent. Its 80% coverage of ice is usually not regarded as part of the West Antarctic ice sheet. By extending northward to within 600 miles of the southern tip of South America, the Antarctic Peninsula presents a major obstacle to the otherwise unimpeded circumpolar circulation of the ocean and atmosphere around Antarctica.

The West Antarctic ice sheet flows into surrounding seas. In westward order from the Greenwich meridian, these are: the Weddell Sea; the Bellingshausen Sea; the Amundsen Sea; and the Ross Sea. These areas will be discussed more in a later section.

3. Geologic setting

Geologists have been forced to piece together the geologic history of West Antarctica on very limited observations of sparse and remote outcrops. They believe that while East Antarctica is primarily a Precambrian craton older than 500 Myr, the West Antarctic ice sheet rests on an aggregate of at least four major crustal blocks created during the Mesozoic breakup of Gondwanaland (Dalziel & Lawver 2001). A combination of ridge-crest subduction and a magmatic plume drove apart these blocks, stretching and thinning the crust with crustal gaps filled with mafic intrusions. This altered crust forms the base of much of the West Antarctic ice sheet. More recent Cenozoic modification possibly caused by plume-driven extensional rifting of the central West Antarctic basin has led to continuing volcanic activity and crustal fracturing.

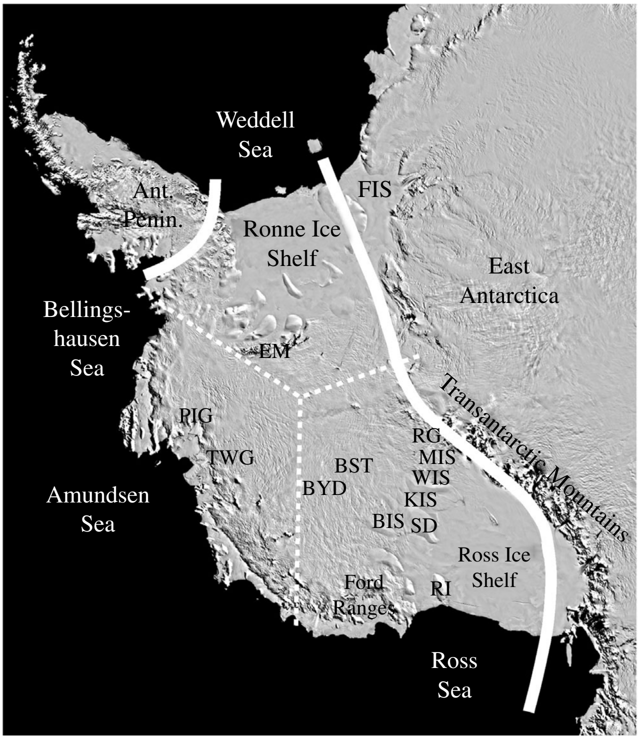

Figure 1. Index map of West Antarctica using MODIS image data (Haran *et al.* 2005). Boundaries at the southern end of the Antarctic Peninsula and along the Transantarctic Mountains (white bold lines) define the West Antarctic ice sheet. Dotted white lines define three sectors of West Antarctica: the Ross Sea sector; Amundsen Sea sector and Weddell Sea sector. Place names: RG, Reedy Glacier; MIS, Mercer Ice Stream; WIS, Whillans Ice Stream; KIS, Kamb Ice Stream; SD, Siple Dome; BIS, Bindschadler Ice Stream; BST, Bentley Subglacial Trench; BYD, Byrd Station; TWG, Thwaites Glacier; PIG, Pine Island Glacier; EM, Ellsworth Mountains; FIS, Filchner Ice Shelf; RI: Roosevelt Island.

4. Surface and basal topography

These tectonic processes have created the present geologic 'cradle' that hosts the present West Antarctic ice sheet. Major topographic divides define three distinct sectors of the ice sheet, each draining in a unique direction and equalling roughly a third of the ice sheet's volume (figure 1). The Weddell Sea sector drains northeastward, around the Ellsworth Mountains and feeds the vast Ronne Ice Shelf (360 000 km^2). The Ross Sea sector drains westward into the even larger Ross Ice Shelf (850 000 km^2), the largest mass of floating ice on the planet. Finally, the Amundsen/Bellingshausen Sea sector drains northward but only small coastal fringing ice shelves exist at its seaward margin.

The highest elevations of the West Antarctic ice sheet exceed 3000 m above sea level and occur along the divides between these three regions. Located near the triple junction of these divides is the site of soon-to-be-drilled ice core for recovery of paleoclimatic information. The average elevation of the ice sheet is considerably lower than that of the East Antarctic ice sheet. Nor are the shapes

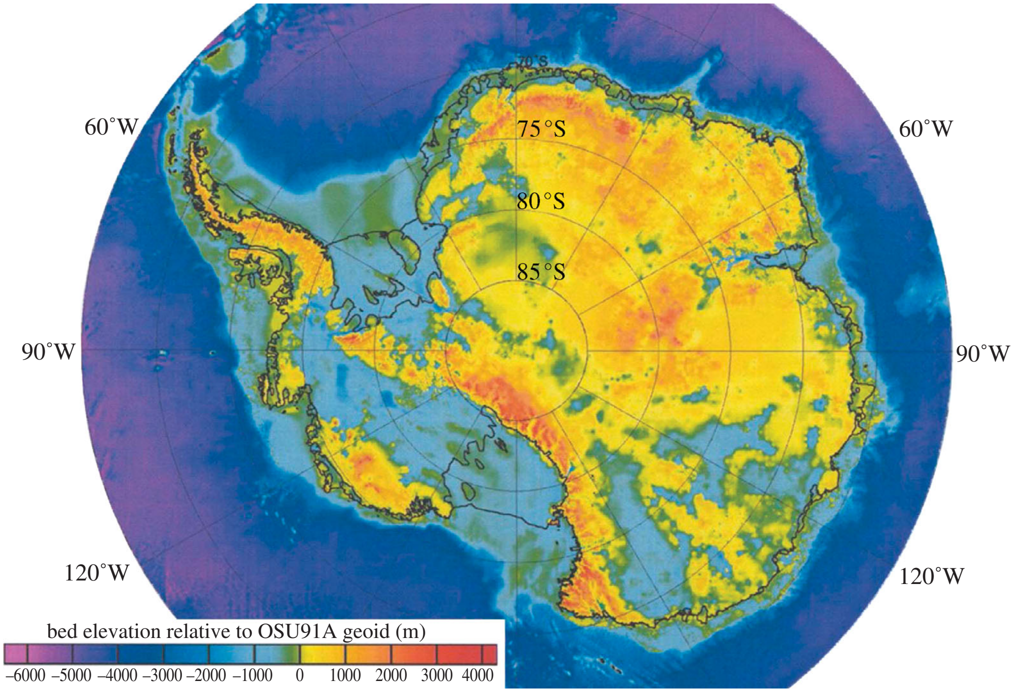

Figure 2. Bed elevation topography from BEDMAP (Lythe *et al.* 2001). Note continental shelf areas and extensive subglacial marine basin of West Antarctica (light blue and green).

of these two ice sheets similar. The East Antarctic ice sheet mostly expresses the roughly parabolic profile of flat interior and increasing slope toward the perimeter. The West Antarctic ice sheet, on the other hand, most often displays a convex-up profile at its interior that reverses curvature to a concave-up profile leading to a progressive flattening onto the ice shelves.

These differences are direct consequences of the different flow regimes of the two ice sheets. Much more snow accumulates in West Antarctica, but the faster speeds return it more quickly to the ocean, limiting the size of the ice sheet. The concave-up surface results from the West Antarctic mode of ice flow where sliding of the ice over the subglacial bed dominates and basal resistance to this flow decreases downstream.

The lower surface elevations in West Antarctica hide the fact that the ice sheet is well over two kilometres thick in many areas. The floor of the geologic cradle is predominantly below sea level (figure 2). These marine basins are variegated with very rough mountainous terrain and flat, deep oceanic basins, such as the Bentley Subglacial Trench that plunges to a maximum measured depth of 2555 m below present sea level. Recent ice sounding measurements are refining the details of the subglacial topography.

More than just giving the West Antarctic ice sheet the moniker 'marine-based' ice sheet, this marine basin is fundamental to concern over the future behaviour of the overlying ice sheet. It was during ancient warm periods of minimal global ice that this basin was filled with water, not ice (Scherer 1991). Marine life within this basin produced a carpet of marine sediment upon the basin's floor that now supports its present cap of ice. Subsequent erosion by ice of exposed basement rocks has created a marine till: a combination of the marine sediment and the glacial till. Sedimentary units up to many hundreds of metres thick have been measured underneath the ice sheet by seismic soundings (Anandakrishnan *et al.* 1998). Direct sampling has been limited to underneath fast flowing ice where the till has been observed to be an unsorted clay-rich diamicton, highlighting the importance of the marine sediment component (Tulaczyk *et al.* 1998). This till is moved by ice motion. In some areas of active ice sliding, the thickness of softest sediment is too thin to measure, basal furrows appear carved out from this bed along the direction of flow and sediment at the end of active flows is layered in beds indicating redeposition (Rooney *et al.* 1987; Alley *et al.* 1989).

Glacial versions of the West Antarctic ice sheet certainly were larger, although there is a range of suggested geometries. Evidence that fast moving ice extended close to the edge of the continental shelf is unequivocal (Anderson *et al.* 1992); however, the question of whether the fast moving ice also extended far into the interior at the same time is still disputed. If it did, then the surface elevation would remain relatively low preventing the ice sheet from being much thicker anywhere than beyond its present margin. Keeping the faster ice a fixed length leads to a much thicker ice sheet. Postglacial rebound data suggest that a large volume of ice has been removed from West Antarctica (Ivins & James 2005), but analyses of globally distributed sea level histories are not always supportive of this interpretation. The largest glacial reconstruction has West Antarctica three times its present size (Hughes 1998) with ice near the deep interior less than 400 m thicker (Steig *et al.* 2001).

5. Meteorology

No ice sheet exists without constant replenishment of mass from the atmosphere. The magnitude and pattern of that replenishment influences the shape and behaviour of that ice sheet. The Antarctic ice-sheet surface lies at a much higher average elevation than any other continent and the presence of such a large mass well into the troposphere forces a persistent clockwise rotation in the southern high latitudes. Synoptic weather systems spawned from perturbations in this general circulation pattern sweep southward. Those that encounter the long and relatively steep orography of East Antarctica are forced to release their moisture near the coast, while those that come ashore in the lower elevations of West Antarctica can penetrate farther inland. As a result, annual accumulation in the heart of West Antarctica generally exceeds 0.1 m (water equivalent units), more than three times the values on the broad plateau of East Antarctica. As with East Antarctica, accumulation rates are generally much higher nearer the coast, but because of the broad low-elevation expanses of the Ross and Ronne Ice Shelves, the 'coast' that eventually forces the moisture from the passing weather systems can lie hundreds of miles from the northward ice shelf edge (see figure 1).

It is impossible to isolate the atmospheric circulation over and around Antarctica from the global pattern. It is not surprising, therefore, that atmospheric variability at other latitudes affects Antarctic weather. A general indicator of the weather pattern in West Antarctica is the position of the persistent polar low

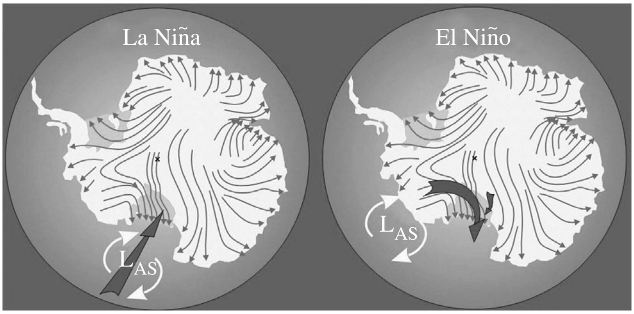

Figure 3. Position of persistent Ross sea low during La Niña and El Niño phases of southern oscillation. Arrows indicate predominant wind direction (from D. Bromwich 2004, personal communication).

over the southern Pacific Ocean. As the global atmospheric pattern shifts through the well known El Niño/La Niña cycle, this polar low's position will oscillate between the Amundsen Sea and the Ross Sea. The result is a general steerage of moisture-carrying air masses into the Amundsen Sea sector or Ross Sea sector, respectively (figure 3). From 1980 to 1990 the Southern Oscillation Index, a measure of the intensity and phase of the El Niño/La Niña cycle, was in phase with the amount of West Antarctic precipitation (quantified by a modelled parameter in atmospheric data reanalysis); however, since 1990, these two parameters have displayed an anti-phase relationship (Bromwich *et al.* 2000). Teleconnection of West Antarctic precipitation with global atmospheric circulation patterns is irrefutable; however, the causal mechanisms are still being researched.

Sea ice extent in the surrounding seas also influences accumulation rate. It is conjectured that the distances that moisture must be carried by ice-sheet bound weather systems is responsible for this connection. West Antarctic precipitation is more than twice as sensitive as precipitation for either East Antarctica or Greenland in this regard, with a 50 km increase in the distance to open water causing a 10% decrease in mean annual West Antarctic precipitation (Zwally & Giovinetto 1997).

Air temperature becomes a critically important factor in ice sheet behaviour when the melting point is reached. The latent heat of melting is equivalent to raising the temperature of one gram of ice 80 K; thus, melting indicates that large amounts of heat have been received. If the water produced from the melted ice penetrates into the ice sheet and refreezes, this heat is released into the ice sheet at the point of refreezing. This has occurred extensively across the Antarctic Peninsula where large ice shelves have disaggregated rapidly (Scambos *et al.* 2000), but is still a relatively rare occurrence in West Antarctica (Das *et al.* 2003). Extended warm periods lasting climatically significant periods take millennia to travel from the top surface of the ice sheet to the basal layers, but when the warmer temperatures arrive, the warmed ice deforms more easily, increasing the flow rate of the ice sheet.

The more immediate effect of warmer air temperatures is an increase in accumulation rates because of the larger moisture holding capacity of the transiting air. While a slight increase in West Antarctic air temperatures has been observed by satellites, there is no definitive increase in accumulation rate documented across the ice sheet (Comiso 2000).

6. Oceanography

The marine bed and large floating ice shelves make the oceanographic aspects of West Antarctica very important. Like the atmosphere, the deep ocean exhibits a strong clockwise circulation around the Antarctic continent. This circumpolar circulation spawns clockwise rotations of the waters in the Weddell and Ross Seas causing surface currents to travel westward across the fronts of the Ronne and Ross Ice Shelves. These broad-scale circulation patterns are also affected by wind stress and tidal forcing.

Beyond the continental shelf, the coldest, densest water circulates at too great a depth to affect the ice sheet. However, there is a water mass, called the Circumpolar Deep Water (CDW) that exists at shallower depths allowing it to move across the continental shelf and reach the seaward extension of the ice sheet. CDW carries enough heat to rapidly melt the undersides of floating ice shelves.

A second water mass involved in ocean–ice shelf interactions is called High Salinity Shelf Water (HSSW). It is generated at the surface on the continental shelf as sea ice forms. Its high salinity makes it denser than other surface water. HSSW may mix with CDW before circulating under an ice shelf. The farther this HSSW/CDW mixture circulates under an ice shelf, the more it is forced downward by the underside shape of the ice shelf. The local freezing temperature is lowered by the larger pressure at depth, causing the relatively warm water to melt ice, freshening the water, making more buoyant 'ice shelf water' (ISW) that rises along the underside of the ice shelf. On its ascent, it can become colder than the local freezing point (this time due to the decrease in pressure at shallower depths), which leads to freezing, extraction of fresh water, making the water more saline and dense. This 'ice pump' can be an effective means of mass transfer beneath ice shelves.

Models of sub-ice shelf circulation are broadly consistent with observations of water properties near the shelf front. The water cavity beneath the Ronne Ice Shelf is deep and supports a strong counter clockwise circulation (Jenkins & Holland 2002). A thick layer of marine ice, several hundred metres thick and believed to have been deposited by this ice-pump mechanism, makes up the lower half of this ice shelf (Oerter *et al.* 1992).

The circulation beneath the Ross Ice Shelf contrasts sharply with the Ronne Ice Shelf. The Ross cavity is much shallower hampering the formation of a persistent shelf-wide circulation pattern and limiting mass exchange rates (Holland *et al.* 2003). The inflow and outflow pattern is complex and seasonally variable.

Few measurements have been made in the Amundsen Sea including any of the depths of the sub-shelf cavities. Large rates of melting have been estimated from measurements of the ice shelf speed and thickness. This has led to values greatly exceeding the few metres per year thought extreme just a few years ago (figure 4). West Antarctic values in the Amundsen Sea sector range from 33 to 43 m per year at the shoreward limit of the ice shelf, where the melting rates should be largest (Rignot & Jacobs 2002).

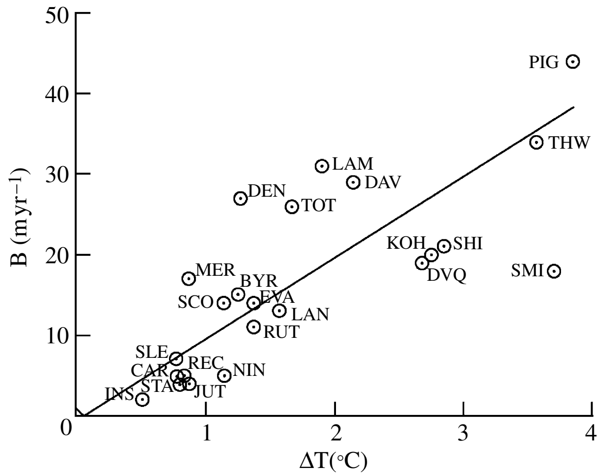

Figure 4. Sub-ice-shelf basal melting rates estimated from mass continuity calculations versus temperature excess (above the freezing point) of adjacent ocean waters (Rignot & Jacobs 2002). Letter symbols are truncated from glacier names. Pine Island Glacier (PIG), Thwaites Glacier (THW) and Smith Glacier (SMI) are outlet glaciers in the Amundsen Sea sector of West Antarctica.

7. Ice streams

So far little has been mentioned about the internal workings of the ice sheet itself. The discussion of the external environment came first because the subglacial material, the replenishment by snowfall and the seaward interface with the ocean are important to understanding ice-sheet flow in West Antarctica. The thin crust beneath most of the West Antarctic ice sheet leads to a relatively high rate of exiting geothermal heat into the marine sediment and the bottom of the ice sheet. This heat produces water that makes the marine sediment soft and allows the ice to slide rapidly. The sliding ice is partially buttressed by the ice shelves, which are fed rapidly with ice upstream, but which also must contend with the warmth of waters circulating beneath. Relatively high snowfall rates drive a high turnover rate of mass within the entire system (Thomas 1973).

The key internal components of the flowing ice sheet are the fast-flowing ice streams and outlet glaciers (figure 5). Nearly all the snow that falls in West Antarctica is eventually funnelled through these critical features. By virtue of their speed, they are the fastest responding elements of the ice sheet and dictate the manner by which the ice sheet responds to changes in its environment. In West Antarctica, whether fast moving ice is labelled an ice stream or an outlet glacier is related as much to when and how each feature was identified as to a deeper appreciation of possible dynamic differences. A glacier's lateral limits are usually taken to be determined by geologic features, such as a mountain valley; an ice stream's lateral limits are defined by marginal shear crevasses, but because ice exists on both sides this boundary, it can move inward or outward, making the ice stream narrower or wider. These differences are not critical to most of the

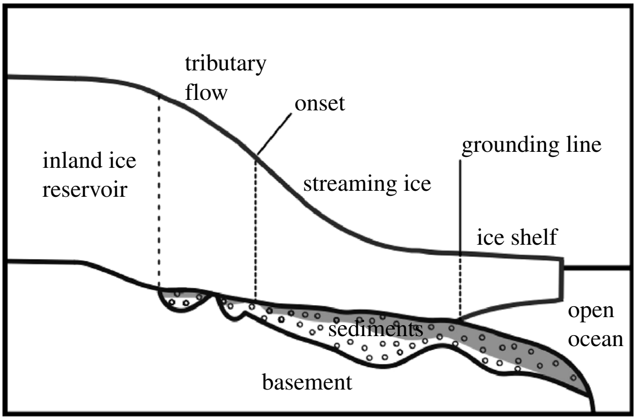

Figure 5. Schematic longitudinal profile of the inland ice/ice stream/ice shelf system identifying location of onset of streaming flow and grounding line (from P. Winberry 2005, personal communication).

remaining discussion where, for simplicity, ice stream will be used as a general term and it is understood that outlet glaciers are included unless a specific distinction is noted.

Ice streams move fast because they rest on a bed of marine till and because the interface with the till is well lubricated. The lubricating fluid is water, produced by the geothermal heat rising through the bed and additionally by friction of the ice's motion against its bed. The rapid motion is a varying combination of ice sliding over its bed and deformation in the upper layers of the till (Kamb 2001). The presence, amount and characteristics of the till probably vary spatially across West Antarctica depending on thermal, hydrologic and geologic factors as well as past ice flow. The fractional contribution of till deformation to total ice stream motion varied from 25% on Whillans Ice Stream to 80% on Bindschadler Ice Stream (Kamb 2001).

The weight of the ice, acting under the force of gravity, forces the ice to flow downhill. This force is counteracted primarily by resistance at the base and the sides of the ice stream. These resistive stresses are discussed in the following sections.

8. Lateral stress

When the bed is well lubricated (an ice shelf is the extreme case), the shearing of ice at the lateral boundaries provides the major resistance to flow. The work done during shearing generates heat that warms the margin making the ice softer and prone to deform even more quickly. This is offset by the cooling effect of slow-moving and colder ridge ice flowing across the margin into the ice stream. Theoretical study indicates the margin can migrate at rates of tens of metres per year (Jacobson & Raymond 1998). Observations have confirmed that margin migration does occur in some locations at roughly these rates.

Mechanically, the resistive forces associated with side shear are transferred through the body of the slower moving ridge to the bed. Specific field studies to detect differences in bed conditions across an active ice stream margin surprisingly showed no difference in water content (Raymond *et al.* 2006). The tentative conclusion is that the transition from the drier bed margin to a wet till under the central ice stream is not sharp.

9. Basal stress

At the ice stream bed, water plays multiple key roles. Not only does it serve as the lubricating fluid for ice sliding, its inclusion in marine till strongly influences till strength. Shear stress, void ratio and effective pressure also affect till strength; an increase in water injection into the till can increase the till's porosity, weakening the till, but deformation of the till can dilate the till leading to an increase in void volume, a decrease in water pressure and a strengthening of the till (Tulaczyk *et al.* 2000). Water also provides a means to transport heat over large distances (Parizek *et al.* 2002). Recently discovered inflations and deflations of the surface suggest cavities of water many kilometres across can fill and drain in a few weeks (Gray *et al.* 2005) (figure 6). The subglacial hydrologic system may well be far more dynamic than previously believed.

The pressure field within the subglacial water system is equally important. The absolute pressure of the system determines what fraction of the weight of the overlying ice is supported by the water. The unsupported portion of ice exerts a normal force on the bed. Water pressures beneath ice streams are usually very close to the weight of the overlying ice. As the water moves, these pressures fluctuate, sometimes exceeding the ice stream's weight, causing the ice to be fully supported by the water and the basal stress to drop to zero.

Most of the water moves along the ice–bed interface, controlled by the hydraulic pressure gradients. These gradients are determined by a combination of ice overburden pressure gradients, related to the ice thickness gradients, and the gravitational potential gradients, related to the bed topography (Shreve 1972). The net result is that surface topography is approximately nine times more important than basal topography in determining the hydraulic pressure gradient, but the inclusion of basal topography means that the direction of subglacial water flow can be different from the direction of ice flow (which follows the surface topography), and changes in the surface topography can alter the flow patterns of ice and water differently.

As with the sides, heat flow is a critical factor in determining the influence of the bed on ice flow. An excess amount of heat can melt basal ice and keep the bed lubricated, whereas a heat deficit will cause water to freeze, removing the lubricating fluid, drying the till and making it stiffer (Tulaczyk *et al.* 2000).

10. Transitions and tributaries

At either end of an ice stream a third resistive force becomes important. When the ice stream enters the ice shelf, basal resistance disappears and the nearby margins are replaced by margins much farther away. These sudden changes would cause a dramatic jump in speed were it not for longitudinal stress acting along the direction of motion, smoothing this transition.

Another transition occurs at the upstream end where ice streams start. This transition is also gradual and takes place within well defined geologic troughs

(Joughin *et al.* 1999; figure 7). The accelerating ice defines 'tributaries' that coalesce into larger faster flows and eventually evolve to ice streams. The tributaries can extend a few hundred kilometres upstream of the ice stream's beginning, or 'onset'. Basal sliding again is the dominant process of ice motion, but the nature of the sliding process is more akin to that found in mountain glaciers, where speed increases as the gravitational stress forcing the ice downstream increases and less to that of ice streams, where speed increases as the gravitational stress decreases. When ice speeds reach about 100 m per year, increased side shear stresses begin to form crevasses (Bindschadler *et al.* 2001).

The positions of onsets may be dictated by the presence of the marine till because they match closely the paleo-shoreline of an ice-free West Antarctic after accounting for the full recovery of the earth's crust after removal of the ice load (Blankenship *et al.* 2001). Alternatively, the gradual increase in basal heat, caused by increased sliding, may determine when the supply of subglacial water is sufficient to sustain an ice stream's fast motion.

The ice streams exhibit a generally straighter flow direction and are steered less by the subglacial topography than the tributaries that feed the ice streams. The paths of ice streams sometime disregard the topography altogether, occupying one side of a deep subglacial valley and not the other side or straddling a portion of a valley and the surrounding elevated terrain (Shabtaie & Bentley 1987). This reinforces the fact that the margins of ice streams can migrate.

11. Temporal changes

Changes in the environment force an ice sheet to change. One of the most confusing aspects of West Antarctic ice sheet behaviour is that change has been observed on many different time scales. This can complicate scientific study and make comparison of data tricky. In this section the various types of change are discussed according to the time scales of each change and the possible causes of that change.

12. Glacial/interglacial

Over the past million years, Earth has experienced waxing and waning ice sheets at roughly a 100 000 year periodicity: 90 000 year-long glacials separated by 10 000 year-long interglacial periods. The West Antarctic ice sheet is known to have been largely absent at least once during the last 400 000 years based on ocean-dwelling diatoms found in subglacial sediments recovered from a site on Whillans Ice Stream, 700 km from the present coast (Scherer 1991). It has not been successfully determined whether the West Antarctic ice sheet survived the last interglacial that peaked about 125 000 years ago. If not, it underscores the importance of the question of why this ice sheet persists when the present interglacial has lasted twice as long as the average.

13. Last glacial

The extent of ice sheets during past glacial periods can be mapped because the post-glacial retreat reveals former subglacial beds and margins. The deep carved troughs that stretch to nearly the edge of the continental shelf around West Antarctica

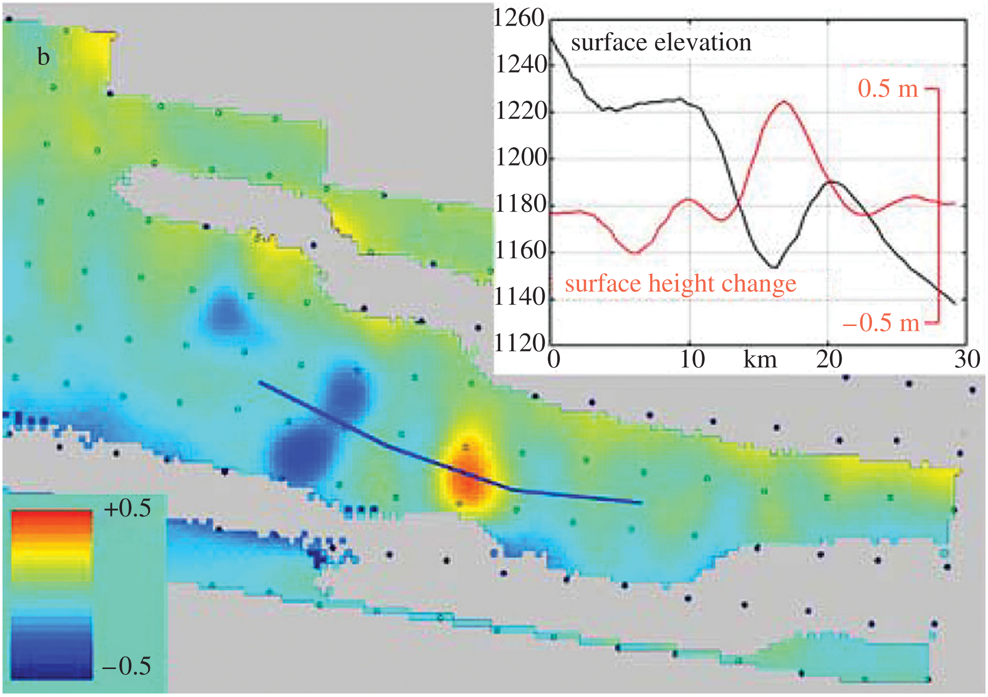

Figure 6. Surface height change over 24 day period from Radarsat of a tributary feeding Bindschadler ice stream in West Antarctica. Colour legend in lower left, profiles along near centre line of region plotted in upper right. Points indicate 5 km grid (Gray *et al.* 2005). Authors attribute inflation and deflation of surface to drainage and filling of subglacial water cavities.

confirm both the former extent of the ice sheet and the former existence of ice streams (Anderson & Shipp 2001). Small, sawtooth-shaped wedges in the seafloor topography may represent brief, possibly even annual, stands of the grounded ice (S. Shipp 2000, personal communication). Ice cored from near the base of Siple Dome indicate past glacial overrunning of this area with the modern dome-type flow emerging about 90 000 years ago (Brook *et al.* 2005).

Ice covering the Ross Sea began its retreat about 11 400 years ago, later than the retreat initiation 18 000 years ago in the Northern Hemisphere and in parts of East Antarctica (Anderson & Shipp 2001). Portions of the retreat were rapid with a retreat hiatus occurring about 7000 years ago when the front was in the vicinity of Ross Island (Conway *et al.* 1999). This hiatus matches the initiation of the Holocene climatic optimum in the Northern Hemisphere, although no climatic connection has been proven.

Thinning, associated with this retreat, has been measured in the near-coastal Ford Ranges. The time previously ice-covered rocks were first exposed to cosmic-ray bombardment can be determined by measuring the concentration of certain cosmic-ray-produced isotopes. Sampling rocks at various elevations within the Ford Ranges showed that the highest summits emerged about 10 400 years ago and the lower summits as recently as 3800 years ago (Stone *et al.* 2003). Thinning is presently continuing. Average exposure time of the Ford Range summits over the more distant past is less than 50% while the lower elevations that are most

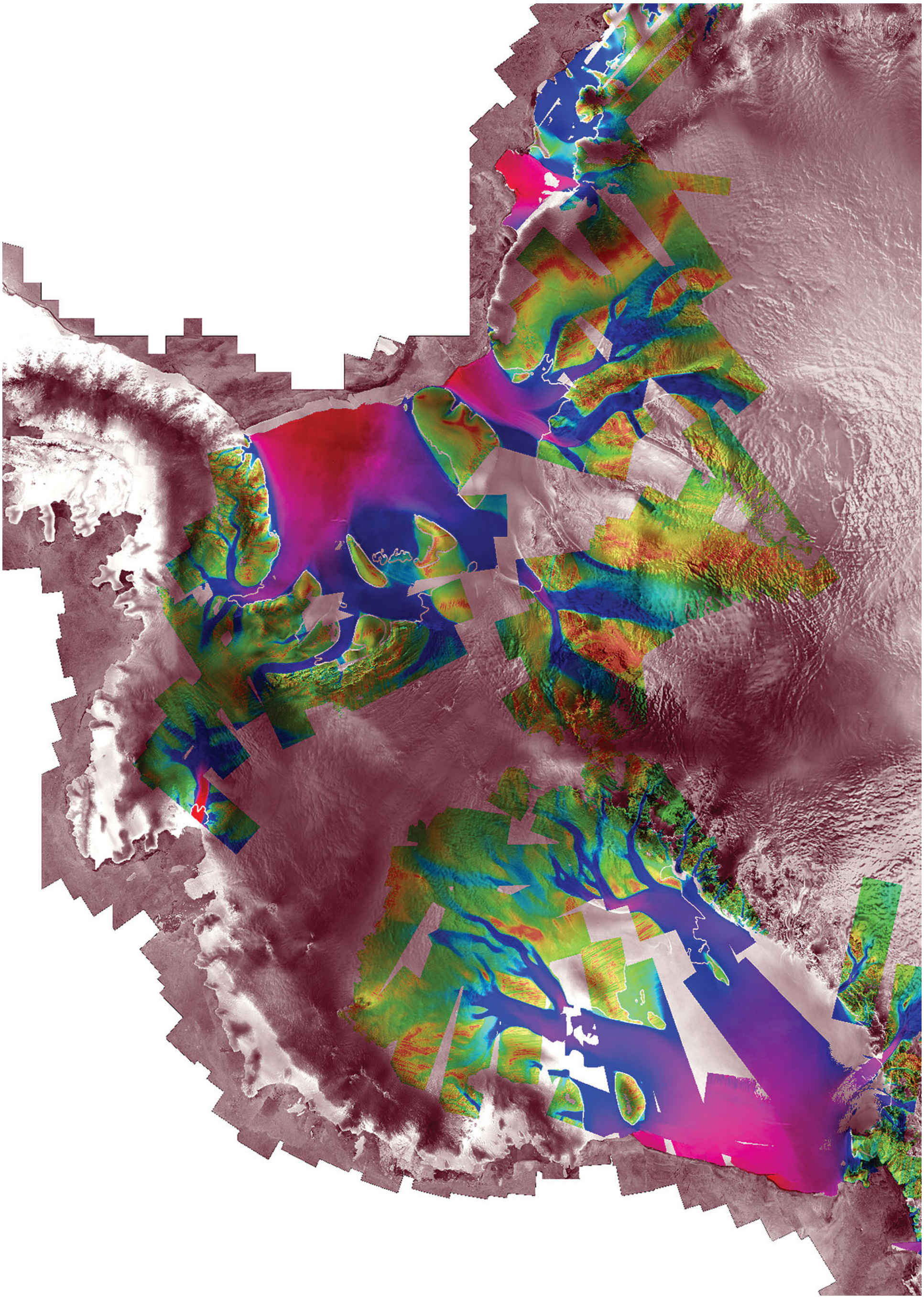

Figure 7. Colour-coded surface velocity from interferometric radar analysis for much of West Antarctica. Velocity increases from less than 100 m a^{-1} (brown, green and light blue) to more than 500 m a^{-1} (magenta and purple). Gray-scale background image is backscatter intensity image from Radarsat data (I. Joughin 2005, personal communication). Plot shows network of tributaries feeding ice streams.

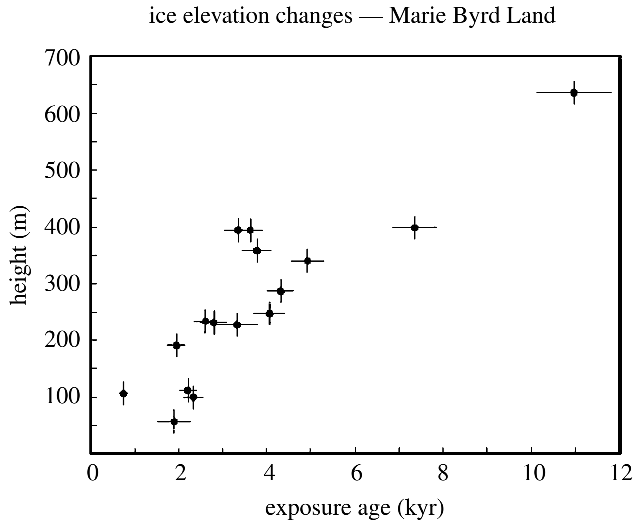

Figure 8. Relative height of upper surface of ice sheet in Ford Ranges of Marie Byrd Land, West Antarctica, versus time from cosmogenic nuclide dating data (J. Stone 2003, personal communication). Plot shows progressive thinning during the past 11 000 years.

recently exposed have been exposed less than 1–5% of the time. (figure 8). This means that the ice extent in this region is at an extreme minimum and probably less than during the prolonged and very warm interglacial 400 000 years ago.

More-interior sites experienced lesser amounts of thinning. Isotopic analysis of ice from Byrd Station indicates it was no more than 400 m higher during the last glacial maximum (Steig *et al.* 2001). Reedy Glacier, at the very southern extreme of West Antarctica, also was only a few hundred metres higher and experienced a more gradual drawdown during the past 10 000 years. Internal layering revealed by ice penetrating radar has been used to deduce that Roosevelt Island was likely overrun by the glacial ice sheet, did not begin to thin until 7000 years ago, and emerged as an ice dome about 3000 years ago, supporting the theory of unsteady retreat (Conway *et al.* 1999).

14. Millennial

Not only is the size of the West Antarctic ice sheet ephemeral; the ice streams within it are also. The fast motion of active ice streams creates crevassed margins and rough surfaces. Past margins have been identified by ice penetrating radars and can be seen in satellite imagery (Rose 1979; Bindschadler & Vornberger 1990). The interstream ridge between Whillans Ice Stream and Mercer Ice Stream is now relatively slow moving, but its rough surface and buried crevasses suggest it flowed at ice-stream speeds sometime in the past (Shabtaie & Bentley 1987).

Distinct paleo-margins identify and define a former ice stream, unofficially dubbed ‘Siple Ice Stream’, that flowed northwesterly across the upstream side of Siple Dome. It was active until about 450 years ago and may have directed

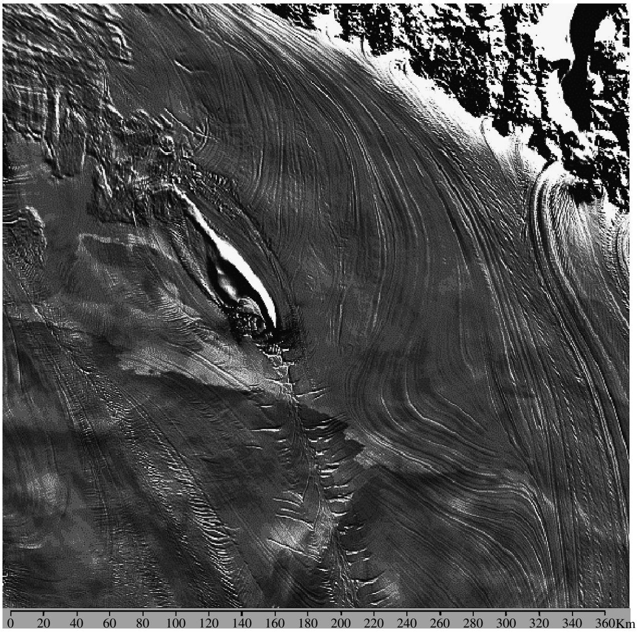

Figure 9. MODIS image mosaic of southern Ross ice shelf showing bowed flow stripes indicating non-steady flow in feeding ice streams (adapted from Fahnestock *et al.* 2000).

the upstream region of Kamb Ice Stream into the downstream region of Bindschadler Ice Stream (Gades *et al.* 2000).

Some former margins are so clearly defined it is unreasonable to expect that they migrated gradually to their present positions (Hulbe & Fahnestock 2004). Thus, the dynamics of ice streams includes the capability for margins to jump distances of many kilometres. It is not known how suddenly this would occur and whether a brief period of inactivity would be required. The self-sustaining aspect of streaming flow, the possible difficulties of restarting a stagnant ice stream, and the observation that near an active margin the subglacial till underneath the ice stream is relatively dry, make it likely that margins can at least jump inward without needing to stop streaming flow.

Surface ridges and troughs that stretch along the length of fast moving ice streams, thus tracing out the direction of flow, aid in disclosing past changes in flow direction. Called 'flowstripes', 'flow traces' or 'streaklines', these features are created by irregularities of either basal topography or basal lubrication. Similar to medial moraines on mountain glaciers, these features align with the velocity field when flow is steady for long periods of time. Misalignment indicates non-steady flow.

Flowstripes being transported across the large Ross and Ronne Ice Shelves provide a means to look back at the flow pattern emanating from the grounded ice streams for the past few centuries. Ice presently near the seaward edge of the Ross Ice Shelf entered the ice shelf about 1000 years ago. Large bowed structures are indisputable evidence of major changes in flow having occurred in the region now fed by the Whillans and Mercer Ice Streams (figure 9). The analysis of this large bowed pattern, other less emphatic flowstripe deviations, and crevassing

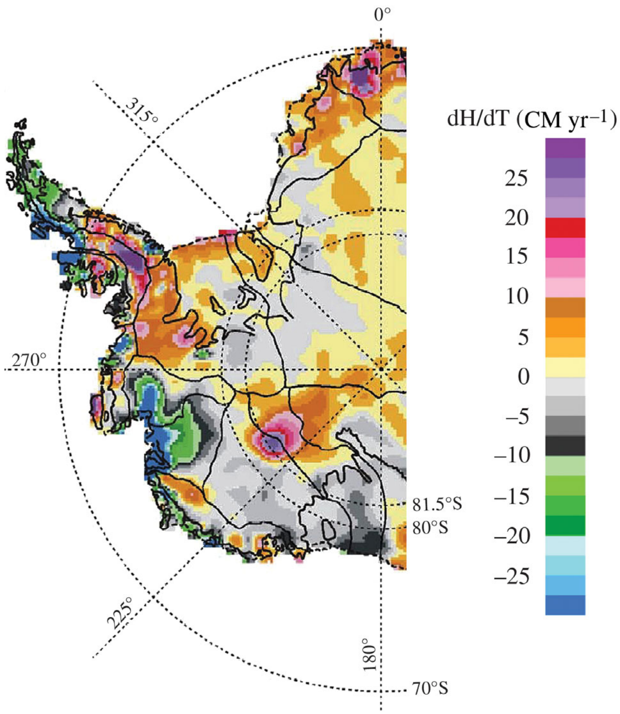

Figure 10. Surface elevation change (1992–2001) from ERS radar altimetry showing localized thickening in the Ross Sea sector, more extensive thinning in the Amundsen Sea sector and little change in Weddell Sea sector (from Zwally *et al.* 2006).

patterns indicate that there were some major flow changes in the southernmost West Antarctic ice streams feeding the Ross Ice Shelf about 550 years ago (Fahnestock *et al.* 2000). Attempts to match other, smaller scale distorted patterns on the Ross Ice Shelf have begun to reveal that the last millennium has witnessed changes in the flow rates of other West Antarctic ice streams (Hulbe & Fahnestock 2004). By contrast, the flowstripes discharged from the East Antarctic ice sheet, through the Transantarctic Mountains into the Ross Ice Shelf and the general pattern across the Ronne Ice Shelf align well with present flow, indicating steady flow direction (Fahnestock *et al.* 2000).

15. Centennial

The most recent known stagnation event in West Antarctica took place on Kamb Ice Stream. The amount of snow covering its once active ice margins indicates it stopped suddenly over most of its length approximately 150 years ago (Smith *et al.* 2002). The tributary system feeding the ice stream remains active, forming a bulge of ice growing at about half a metre per year and unable to exit the ice sheet. How the growth of this bulge will evolve and whether the lower ice stream will reinitiate are ongoing research questions motivating sustained field observations.

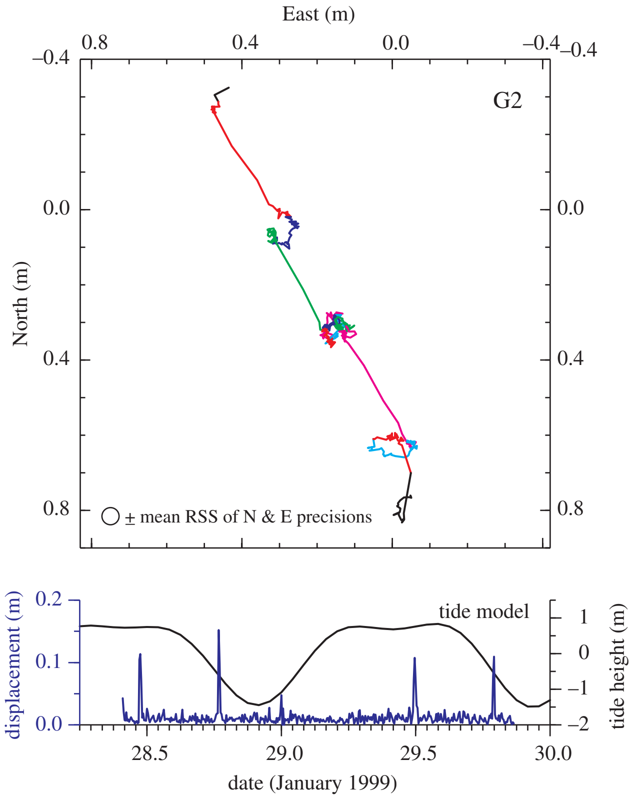

Figure 11. Stick slip motion of the mouth of Whillans ice stream recorded by GPS receivers. Upper plot shows position every 5 min with colour change every 2 h. Lower plot shows modelled tide (black line) and horizontal displacement every 5 min (blue line) (adapted from Bindschadler *et al.* 2003).

There also has been speculation about what caused this stagnation. The present geometry is diverting subglacial water from flowing underneath Kamb Ice Stream to flowing south into the still-active Whillans Ice Stream. One theory claims that this diversion caused stagnation of Kamb Ice Stream. Another theory disputes this, contending that the hydrologic diversion was a consequence, rather than a cause, of the stagnation and that the ice stream thinned enough to freeze basal water, stiffen the till and stop the stream, forcing upstream water to go elsewhere (Anandakrishnan *et al.* 2001).

16. Decadal

Intensive field studies of the flow of West Antarctica began in the early 1980s and satellite data extend back to the early 1960s, allowing direct measurements of change on the decadal time scale. Acceleration, deceleration and steady flow are all observed. Curiously, these three different regimes of change occur distinctly in the three different geographical regions of West Antarctica.

Acceleration is most commonly observed in the Amundsen Sea region. Pine Island and Thwaites Glaciers (THW) and some of the much smaller outlet glaciers are accelerating at rates of a few percent per year (Rignot & Schmeltz 2002). These rates cannot have been sustained for decades without there being many far ranging and observable changes elsewhere. Thus, they are likely a recent occurrence.

Velocities are decreasing across the entire Whillans Ice Stream at the typical rate of 1–2% per year over the past two decades (Joughin *et al.* 2002). Slightly higher rates have been observed downstream where basal freezing is likely, implying that the removal of water is making the till stiffer, increasing the basal resistance to flow. It is possible this deceleration will result eventually in stagnation of the ice stream.

In the Weddell Sea region, no sustained changes in flow speed have been observed over this same multi-decadal period.

Surface elevation measurements by satellite altimeters show a pattern of change consistent with the spatial pattern of velocity change: the Amundsen Sea sector is thinning; the Ross Sea sector is thickening; and the Weddell Sea sector is roughly in equilibrium (Zwally *et al.* 2006; figure 10). The thickening in the Ross Sea sector is primarily the result of the stagnant Kamb Ice Stream. Based on the most recent laser altimetry results, the decelerating Whillans Ice Stream is now contributing to this thickening, while the other active ice streams are thinning slightly (Smith *et al.* 2005). In the Amundsen Sea sector, there are major changes taking place in many of the outlet glaciers (discussed below); however, THW stands out as a major outlet whose current flow is considerably different from what accumulation and geometry suggest should be the discharge pattern of this glacier (Bamber & Rignot 2002).

17. Daily

Ocean tides have a surprisingly large effect on ice stream motion. Precise global positioning system (GPS) positions indicate that where ice streams enter both the Ronne and Ross Ice Shelves ice flows about 10% faster during periods of spring tides (G. H. Gudmundsson 2005, personal communication). In the Ross Sea sector, there is even more dramatic sensitivity: most of the lower ice streams accelerate to flow 50% above their mean speed during falling tides with a symmetric deceleration to speeds approximately 50% below the average during rising tides (Anandakrishnan *et al.* 2003). The notable exception is Whillans Ice Stream which exhibits stick-slip motion: most of the motion occurs during two brief episodes lasting 20–30 min during falling tide. During these slip events, speed corresponds to that expected for a completely lubricated bed and the acceleration and deceleration require no more than one to a few minutes (Bindschadler *et al.* 2003; figure 11). In all cases of tidal modulation, the phenomenon decays gradually upstream, but can still be detected more than 100 km from the grounding line.

The timing of the stick-slip events can be reproduced by a simple, plastic bed model where the slip occurs after a threshold strain is exceeded but this timing can be improved with a rate-dependent slip threshold (Bindschadler *et al.* 2003; P. Winberry, personal communication). It is probably important that the only ice stream exhibiting stick-slip is also the ice stream presumed to be experiencing strong basal freezing of basal water. It is unlikely that the tidal variations actually transport water significant distances under the ice. The tidal effects are probably transmitted either via pressure through the subglacial hydraulic system or by longitudinal stresses within the ice. A more complex model is needed to explain the gradational response of the other ice streams.

18. A glimpse of the future

Satellite sensors have revealed the multiple facets of a rapidly shrinking ice sheet in the Amundsen Sea region where Pine Island and THWs are the major outlets. Both they and their neighbouring glaciers are accelerating and thinning most rapidly nearest the coast (Shepherd *et al.* 2004). This is the pattern expected of an ice-sheet collapse. Recent airborne observations establish that thinning is accelerating (Thomas *et al.* 2004; figure 12). The consistent and widespread pattern suggests external forcing. Nearly none of the former Pine Island Bay ice shelf remains and the extent of the fringing sea ice cover is decreasing (Jacobs & Comiso 1997). These may be prescient observations because the larger magnitude changes at the coast suggest that they are at least partly driven by the influx of warmer waters up onto the continental shelf, where currents lead them to interact with the underside of the ice shelf and other floating ice.

Extensive warming on the Antarctic Peninsula has led to the sudden disintegration of individual ice shelves along both east and west coasts by a process driven by intense summer melting. In one monitored case, ice upstream of a removed ice shelf accelerated in agreement with the theory contending that the grounded portion of the West Antarctic ice sheet is buttressed by the ice shelf and that removal or thinning of the shelf will lead to acceleration and thinning of the grounded ice (Scambos *et al.* 2000). The present behaviour of the ice sheet in the Amundsen Sea sector also conforms to this pattern. Presently, the Ross and Ronne Ice Shelves have experienced only occasional summer melting. Many more degrees warming will be required to increase the frequency and the intensity of summer melting on these ice shelves to the point of endangering them (Vaughan & Doake 1996).

Research on the dynamics of the West Antarctic ice sheet is intended to produce knowledge of the important processes so that predictions of the future behaviour of the ice sheet can be made well in advance of dramatic change to the ice sheet and to global sea level. Numerical models are the tools to make these predictions of the future. Models of the West Antarctic ice sheet with variable grids can include adequate resolution to capture the important features but they do not yet include all the complex interactions between ice, till and water in ways that reproduce the observed and inferred behaviour on the variety of time scales known from observations. Recent models have achieved an ability to simulate ice stream stagnation and reactivation through thermal triggering and are also becoming better at matching the variety of field data of motion, flow history and temperature structure (Hulbe & Payne 2001). The compelling importance of knowing the heat budget requires these models to be fully thermodynamic. Also, the importance of water in its several roles also requires calculation of not only water balance, but also subglacial water flow. These are challenges that will be met as knowledge of the dynamics of the West Antarctic ice sheet improves.

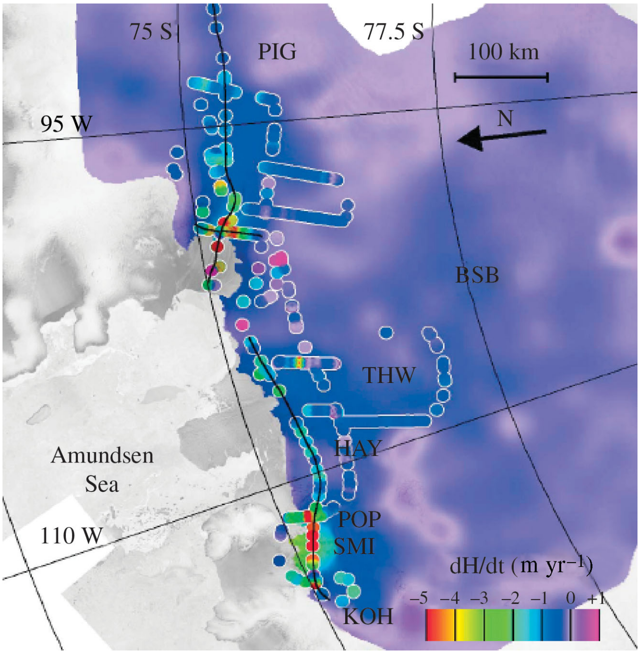

Figure 12. Ice thickness change (derived from elevation change) from satellite radar altimeter for the period 1992–2000 (background colours) and from airborne laser altimetry in 2004 (coloured dots). Where dot colour differs from surrounding colour, a change in rate of thickness change has occurred. Plot indicates accelerating thinning in many regions (Thomas *et al.* 2004).

19. Summary

The Intergovernmental Panel on Climate Change characterized a collapse of the West Antarctic ice sheet as a 'high risk, low probability' event (IPCC 2001). Scientific studies of the ice sheet's behaviour and its environment have greatly elucidated the nature of the interactions between the ice sheet and its environment. The first conclusion is that the entire system is far more complex than believed, making it difficult to achieve an accurate prediction of future behaviour on any initial timetable.

The interdependencies have revealed positive and negative feedbacks that are still being integrated into numerical models. Other measurements have revealed a host of changes on nearly every conceivable time scale. Other processes await additional measurements. Nevertheless, as the body of accumulated measurements increases, the ability of models to accurately simulate observed behaviour increases, using verified processes where possible and resting on parameterized hypotheses where necessary. The importance of gradually improved predictions mandates that this effort continue with full appreciation of the limitations of each prediction.

This overview paper can never hope to give adequate credit to the vast numbers of people whose hard work studying the West Antarctic ice sheet have revealed a fascinatingly complex region of the world. Charles Bentley and Richard Alley provided excellent reviews that were instrumental in vesting improving the original paper.

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