PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

Phil. Trans. R. Soc. A (2006) **364**, 1867–1872
doi:10.1098/rsta.2006.1802
Published online 25 May 2006

Evolution of the Antarctic ice sheet: new understanding and challenges

By Antony J. Payne[1,*], Julian C. R. Hunt[2] and Duncan J. Wingham[2]

[1]*Centre for Polar Observation and Modelling, University of Bristol, Bristol BS8 1SS, UK*
[2]*Centre for Polar Observation and Modelling, University College London, Gower Street, London WC1E 6BT, UK*

This brief paper has two purposes. First, we gauge developments in the study of the Antarctic ice sheet over the last seven years by comparing the contents of this issue with the volume produced from an American Geophysical Union meeting, held in September 1998, on the West Antarctic ice sheet. We focus on the uptake of satellite-based observation; ice–ocean interactions; ice streams as foci of change within the ice sheet; and the time scales on which the ice sheet is thought to operate. Second, we attempt to anticipate the future challenges that the study of the Antarctic ice sheet will present.

We highlight the role of the upcoming International Polar Year in facilitating a better coverage of *in situ* climatic observations over the continent; the pressing need to understand the causes and consequences of the contemporary changes observed in the Amundsen Sea sector of West Antarctica; and the need for improved physics in predictive models of the ice sheet.

Keywords: Antarctica; climate change; glaciology; satellites

In this brief paper, we have two main aims: to review our current understanding of the present-day evolution of the Antarctic ice sheet; and to highlight the specific challenges that remain. A useful approach to the former is to contrast the papers contained in this volume and those presented at the discussion meeting with results presented at the last major scientific meeting to focus on the Antarctic ice sheet. This was the American Geophysical Union's Chapman meeting on the West Antarctica ice sheet (WAIS) in September 1998 and the associated volume (Alley & Bindschadler 2001; hereafter referred to as the WAIS volume).

Four main distinctions between the two volumes are immediately evident. These are: the growth in work based on satellite observation of the ice sheet; the identification of interactions with the ocean as a key control on ice-sheet evolution; a movement away from the analysis of the controls on ice-stream motion to research on their response to external perturbation; and, finally, a recognition that significant parts of the ice sheet can change on decadal time scales. We will now focus on each of these developments in turn.

* Author for correspondence (a.j.payne@bristol.ac.uk).

One contribution of 14 to a Discussion Meeting Issue 'Evolution of the Antarctic Ice Sheet: new understanding and challenges'.

Satellite-based measurements play a limited role in the WAIS volume. Fahnestock & Bamber (2001) make use of two types of satellite data: radar altimetry (RA) from the European Remote Sensing (ERS) satellite and velocity estimates derived from feature tracking using Landsat imagery. Bindschadler *et al.* (2001) apply the latter technique in their study of the ice streams of the Siple Coast. In contrast, the discussion meeting was dominated by discussion prompted by satellite observation. Two main workhorses are responsible for this revolution. The first is repeated RA based on ERS data, which allows high-accuracy, spatially extensive measurements of ice thinning to be made (on the justifiable assumption that changes in ice-surface elevation are a consequence of ice-thickness change rather than changes in the elevation of the underlying bedrock). This technique has been applied to estimate the mass balance of the entire ice sheet (Wingham *et al.* 1998; Davis *et al.* 2005; Wingham *et al.* 2006*a*), as well as that of localized components of the ice sheet such as ice shelves (Shepherd *et al.* 2003) and ice streams (Shepherd *et al.* 2001). The second technique is that of synthetic-aperture radar interferometery (SRI) using data from the ERS and RADARSAT satellites, which is used to measure (again to very high accuracy and over very wide areas) the velocity of the ice surface in the horizontal plane, as well as its vertical motion. Examples of the application of SRI to determine horizontal ice velocity are numerous and are often the basis of the budgeting approach to mass balance, whereby the flux of ice leaving an ice mass (approximated by the product of SRI velocity and ice thickness) is compared to that entering via snow accumulation (Rignot 2006).

When combined, these two techniques can be very powerful in constraining the possible causes of an observed phenomenon. Examples include recent work on the sporadic nature of subglacial water drainage (which is observable by its effect on the local warping of the ice surface) reported by Gray *et al.* (2005) and Wingham *et al.* (2006*b*) and analysed by Evatt *et al.* (2006). Another excellent example comes from work on the recent dynamics of Pine Island Glacier. The original observation of change in this area by RA (Wingham *et al.* 1998) was immediately followed by SRI observations of tidal flexure of the area's floating ice shelf and, more specifically, the retreat of the ice shelf's grounding line (Rignot 1998). Joughin *et al.* (2003) use SRI to measure horizontal velocity at various epochs during the 1990s to show that grounding-line retreat was associated with distinct phases of ice stream acceleration. The impact of this acceleration on the ice stream of Pine Island Glacier was measured using RA by Shepherd *et al.* (2001) with the interesting result that the thinning signal extended hundreds of kilometres upstream. Finally, Shepherd *et al.* (2004) use RA to measure the thinning of the area's ice shelf, with the implication that this thinning is responsible for the grounding-line retreat and the acceleration and thinning of Pine Island Glacier itself. It is therefore true to say that satellite observations have matured sufficiently since 1998 to dominate the research agenda in large-scale Antarctic glaciology and now provide the key observations that then prompt either theoretical analysis or detailed field and airborne campaigns.

We now turn to the second of our contrasts with the WAIS volume. Prompted partly by the line of evidence alluded to above in relation to Pine Island Glacier, it is now clear that the interaction between an ice sheet and its adjoining ocean is crucially important in determining the evolution of the ice sheet. Numerical modelling studies have long highlighted the importance of the melt rates experienced by ice shelves in controlling the growth and retreat of the Antarctic ice sheet over glacier–interglacial cycles (e.g. Huybrechts 2002). However, this sensitivity has not been recognized in studies of the contemporary ice sheet, to the extent that no paper in the WAIS volume focused on ice–ocean interactions or variations in the Southern Ocean. The undoubted importance of changing snow accumulation patterns for Antarctic ice volume and global sea level is the subject of papers in both the current and WAIS volumes (Bromwich & Rogers 2001; Monaghan *et al.* 2006). However, the science here is relatively well understood and predictions are reasonably well bounded, while the processes likely to cause oceanographic change, their effect on ice shelves and the impact of thinning floating ice on the grounded ice masses of Antarctica are all poorly understood and offer no basis on which predictions can be made. Steps towards understanding this complicated series of interactions are provided by Hindmarsh (2006) and Jacobs (2006).

The majority of the WAIS volume is concerned with understanding the mechanics of ice streams, in particular those of the Siple Coast, as well as the factors controlling their development from tributaries, lateral migration and occasional stagnation. Many of the papers summarize results from an extremely successful series of field campaigns involving radar-echo sounding, seismic survey, ice drilling and subglacial instrumentation. These papers (along with that of Tulaczyk *et al.* 2000) highlight the importance of deformable, water-saturated subglacial sediment in determining the location of ice streams, as well as the intimate link between subglacial hydrology, basal thermal regime and sediment deformation. As a result of this work, many of the issues of the maintenance, migration and stagnation of ice streams are now thought to be reasonably well understood; however, recent satellite-based observations have now focused attention on the response of ice streams to external perturbation (see below).

The final distinction that we wish to draw with the work collected in the WAIS volume is that of time scale. The WAIS volume itself reflects a significant shortening of the time scales thought appropriate to the study of ice sheets from a position where ice sheets were seen as passive elements within the climate system (with typical time scales of tens of thousands of years) to a recognition of ice-stream variability on the time scale of hundreds to thousands of years (e.g. Anandakrishnan *et al.* 2001). In the intervening decade, it has become clear that even shorter time scales are appropriate to the study of ice streams. In particular, Payne *et al.* (2004) show that the response time of ice steams, such as Pine Island Glacier, may well be as short as a decade. Further, recent work pioneered by Bindschadler *et al.* (2003) shows a clear tidal signal in the flow of ice streams.

We now turn to the challenges that we believe that the discussion meeting has presented to the Antarctic research community. Some are technical in nature, such as extending the capability of the present generation of altimeter satellites to cope with areas of steep surface slopes, which are typically found close to the coasts and are where most change (in terms of both varying accumulation patterns and changing ice flow) is believed to be occurring. The loss of the CryoSat satellite shortly before the discussion meeting is particularly relevant here, as is the recently announced approval for a replacement mission. A second challenge of this nature is to extend the *in situ* observational system for both meteorological change and, perhaps more importantly bearing in mind the paucity of the current data base (Jacobs 2006), oceanographic change. A system of automatic weather stations and permanently moored buoys could be supplemented by autonomous vehicles for long-range atmospheric, oceanographic and glaciological observation. Perhaps the greatest challenge in this area will be obtaining information from beneath the ice shelves on the interaction of ocean water with the underside of these floating ice masses. Although considerable advances have been made in improving the spatial density of *in situ* observations, Antarctica remains by a great distance the most poorly instrumented of continents. The approaching International Polar Year offers a very significant opportunity to fill many of the lacunae in the observational record of the continent.

More fundamentally, the grand challenge is to determine the cause of contemporary glaciological change in Antarctica (with its direct effect on global sea levels) with the need to determine whether this change is ultimately anthropogenic or due to natural variability. While satellite observations have revolutionized our knowledge of contemporary glaciological change, they will remain limited in that the record can only be extended forward from the early 1990s. Given this narrow window of one to two decades' observation, the question remains: is the variability that we observe particular to the late 1990s and anthropogenic in origin or would such variability be observed in a decadal sample of random date and therefore primarily reflects natural variability? Eventually, the record will approach the natural time scales of the ice sheet and its ice streams and ice shelves; however, society is unlikely to have the luxury of waiting for the necessary time to elapse before it takes action. Clearly, the strengths of satellite observation must be combined with other data to provide a quicker answer. Data assimilation offers one potential way forward that was explored during the discussion meeting. This technique provides a formalism by which satellite observation (in particular, RA and SRI) can be combined with other data (such as the century-long accumulation records available from snow pit records) to provide an optimal estimate of Antarctica's state of balance. The paper by Arthern & Hindmarsh (2006) offers an early example of the application of this technique. More widely, data assimilation can be used with satellite observations in an inverse geophysical approach to constrain unobserved parameters. Examples are papers by Joughin *et al.* (2006) who determine the spatial distribution of the basal traction controlling ice-stream flow and Vieli *et al.* who investigate the controls of ice rheology on ice-shelf flow.

Finally, a theme that the discussion meeting returned to repeatedly was the inadequacy of the present generation of ice sheet models. These large-scale models were generally developed in the 1990s and the basic physics that they contain has changed little since that time. Many of the observations highlighted during the meeting are not reproduced by these models, indeed it seems very likely that the underlying physical processes responsible for the observed phenomena are not contained within such ice-sheet models. Four main areas of concern were discussed. First, there is evidence that the present generation of atmospheric models are unable to capture the temporal variations in snowfall whose effect is apparent in new RA observations (Wingham *et al.* 2006*a*). Second, much of the variability seen in present-day Antarctica is associated with the behaviour of ice streams, which have a typical width of approximately 40 km. Contemporary ice-sheet models of the type commonly used to make sea-level predictions typically operate at a 20 km horizontal resolution; ice streams are therefore barely resolved. A more significant concern is that the stress regimes believed to operate within ice streams, their shear margins and their tributaries are very much more complex than that employed in the numerical models. Higher-order models of ice-flow do exist; however, to date they have only been applied to isolated ice streams. A challenge to the numerical modelling community for the next few years will be the application of this type of model in whole ice-sheet simulations. This is thought to be critical because many of effects that we believe to be important in determining the response of an ice sheet to changes within an adjoining ice shelf rely on the transmission of longitudinal stresses (see Hindmarsh 2006). A third shortcoming of the present generation of large-scale models is that changes in subglacial hydrology and their effect on the rheology of subglacial sediments are not incorporated. The stability of ice streams is now thought to depend largely on the availability of easily deformed, water-saturated subglacial sediment; their long-term evolution (and therefore that of the ice sheet) cannot therefore be modelled without the incorporation of these subglacial processes into ice-sheet models. Finally, there are the issues related to the modelling of the interactions between ice and ocean. Many questions remain relating to the ability of the current generation of models to simulate grounding-line migration in a rigorous manner (see Hindmarsh 2006). Of equal importance for the future will be the need to improve the coupling between the floating ice and ocean dynamics. Currently, melt rates are prescribed whereas they should be determined by detailed modelling of the ocean water moving between the coastal ice zone and the open ocean.

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