The AMISOR project: ice shelf dynamics and ice-ocean interaction of the Amery Ice Shelf

Ian Allison

Antarctic CRC and Australian Antarctic Division, Private Bag 80, Hobart, Tasmania, 7001, Australia

Abstract

The Amery Ice Shelf (70°S, 70°E) is the third largest embayed shelf in Antarctica, and the largest entirely within East Antarctica. This ice shelf has been studied by the Australian Antarctic program for more than 50 years, although only in the past decade has the importance of ice–ocean interaction beneath the shelf become fully apparent. This has led to the establishment of a project of "Amery Ice Shelf Ocean Research (AMISOR)". This multidisciplinary project has overall aims of quantifying the interaction between the ocean and the Amery Ice Shelf (AIS); and determining the implications of this interaction for the discharge of grounded ice and to water mass modification. The project includes components of hot-water drilling through the AIS to make measurements in the underlying cavity; glaciological measurements of the ice shelf velocity, strain and thickness; oceanographic measurements in Prydz Bay; investigation of sub ice shelf sediments and sediment dynamics; remote sensing; and numerical modelling of ice shelf-ocean interaction and ice shelf dynamics. This paper provides a brief review of past and present Australian research on the AIS, with an emphasis on the AMISOR activities.

1. Background

The Amery Ice Shelf (AIS) has a total surface area of 71,260 km^2 (Fricker et al., 2002a). It drains the grounded ice from the interior of the Lambert Glacier drainage basin, which covers an area of 16% of the East Antarctic ice sheet. The AIS has been the focus of considerable investigation by the Australian National Antarctic Research Expedition (ANARE) since as early as the mid 1950s. It was described from aerial reconnaissance during early ANARE exploration (Mellor and McKinnon, 1960), and between 1962 and 1964, over-snow traverses from Mawson station undertook a glaciological survey along a 200 km line parallel with the longitudinal axis of the shelf, and on two transverse lines. The positions of a few key marker canes on these lines were determined from astronomical observations and then resurveyed in a later year to determine the ice shelf motion. Grids of cane markers at these key points were accurately measured to determine the strain rate, and the surface elevations along the routes were determined barometrically. Results from this project (Budd et al., 1967) showed that the speed of the ice shelf increased from 300 m a^{-1} opposite Beaver Lake (70.8°S, 68.3°E) to about 1500 m a^{-1} near the calving front, and that the snow accumulation decreased rapidly with distance from the ocean. These and the other results were used to validate estimates of the ice shelf velocity and strain derived from a generalised theory of ice shelf dynamics (Budd, 1966).

These exploratory surveys laid the ground for a more intensive study of the shelf in 1968 by a small over-wintering party stationed at G1 (69.5°S, 71.5°E) about 60 km from the front of the shelf. During the 1968 expedition, and a subsequent resurvey in the 1969/70 summer, 88 ice velocity measurements were made using electronic distance measuring equipment and theodolite on a 500 km network of survey lines along and across the shelf. The ice shelf surface elevation was accurately measured by optical levelling and, in the 1969/70 summer, the first ANARE measurements of ice thickness using a radar system were made. The first ANARE thermal ice-drilling program was also undertaken and a 315 m deep ice core was recovered from G1. Results from this project were summarised by Budd et al. (1982)

(Figure 1). The ice shelf dynamics and mass budget were detailed and, at that time, the AIS was probably the most extensively studied of all ice shelves. Oxygen isotope and salinity analysis of the ice core from G1 showed a 3-layer structure. The top 70 m were derived from snowfall on the ice shelf; from 70 m to 270 m depth the ice was much older, originating from the grounded ice sheet further inland; and the bottom of the shelf was marine ice that had frozen directly from the underlying seawater (Morgan, 1972). The same 3-layer structure was seen in the crystal structure of the ice core (Wakahama and Budd, 1976). The ice frozen from seawater contains traces of marine organic material and gives rise to the spectacular jade-coloured icebergs frequently seen in Prydz Bay and to the west (Warren et al., 1993).

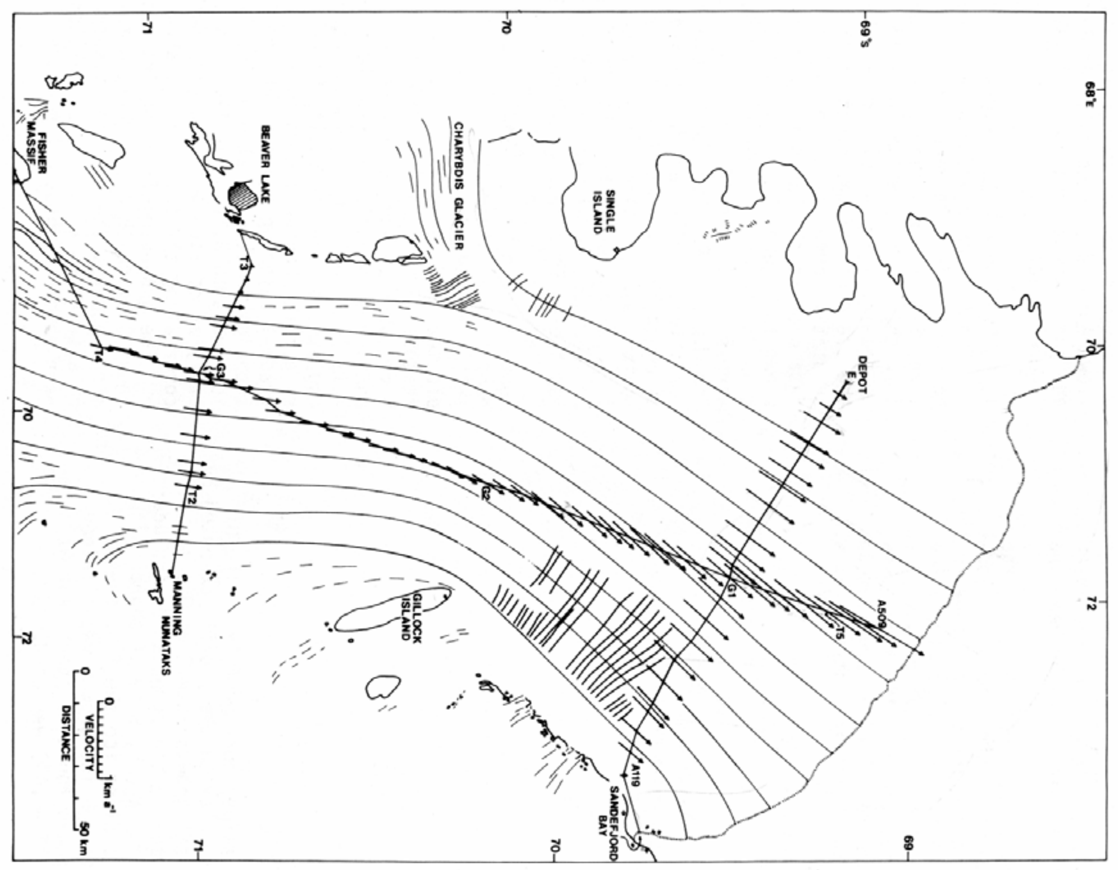

Figure 1 Traverse routes surveyed during the 1968 Amery Ice Shelf Project, showing measured ice movement vectors and flow-lines derived from Landsat imagery. [Budd et al., 1982]

From the longitudinal profile measured in 1968-70, Budd et al. (1982) deduced that the transition between floating and grounded ice occurred 3 km south of T4 (71.2°S, Figure 1). In the early 1970s, measurements of ice velocity and ice thickness were made inland of the major ice streams draining into the AIS. The ice mass flux derived from these (Allison, 1979) was considerably greater than the flux through the floating AIS just downstream of T4, suggesting that, if the ice shelf was grounded at T4, the interior ice sheet was in a state of positive imbalance.

The Amery was the focus of renewed activity in the late 1980s and early 1990s as part of an overall study of the Lambert drainage basin (Higham and Craven, 1997; Craven et al., 2001; Kiernan, 2001). Much of this work was done in the region of the ice shelf near G3 and T4, where the grounding zone was believed to be located. Airborne radio echo sounding measurements of ice thickness were made both from a helicopter and from a Twin Otter aircraft, and GPS equipment was used for the first time, both for flight navigation and ice movement surveys (Manson et al., 2000).

2. Remote sensing of the ice shelf dynamics and mass budget

In the early 1990s, satellite radar altimeter measurements became available from the ERS-1 satellite. A digital elevation model (DEM) of the Amery Ice Shelf and Lambert Glacier basin was derived using the satellite altimetry (Fricker et al., 2000). This was validated against surface elevations measured by a precise kinematic GPS survey made during a skidoo traverse of part of the shelf in 1995 (Phillips et al., 1998). Using a combination of the Amery DEM, extensive ice thickness measurements from ANARE and Russian field surveys, and a simple firn-ice density model, the extent of the floating ice was mapped by a hydrostatic calculation. This revealed that the ice is actually floating as far south as 73.2°S near Mawson Escarpment, about 240 km further upstream than previously reported (Fricker et al., 2002a). This result was confirmed by static GPS measurements that show vertical tidal motion at 72.98°S. Other evidence for the grounding zone position came from an analysis of satellite imagery, mass flux calculations, and ice radar data.

A significant hydrostatic anomaly was also observed in the northwestern quadrant of the ice shelf due to an extensive marine ice layer. Ice radar soundings do not penetrate the marine ice because of the presence of conductive brine, and hence the ratio of surface elevation to the measured thickness is not what is expected for floating ice. The thickness distribution of accreted marine ice, predicted to be up to 190 m thick in places, was estimated from the anomaly by Fricker et al., 2001 (Figure 2).

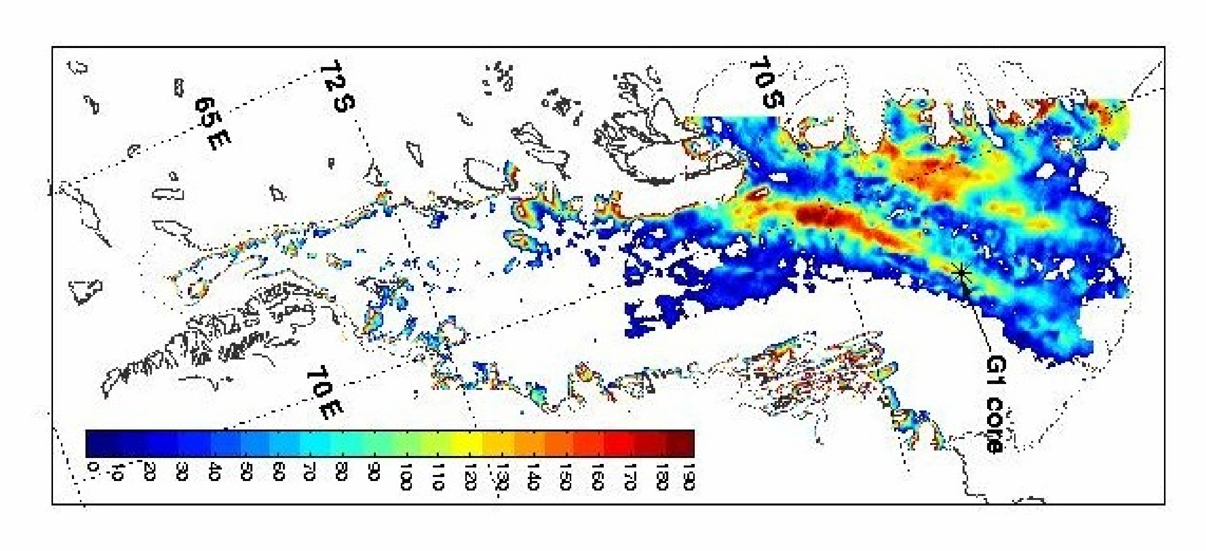

Figure 2 Distribution of the thickness of accreted marine ice underneath the northwestern quadrant of the Amery Ice Shelf (metres) [Fricker at al., 2001]. Other regions where hydrostatic equilibrium is not satisfied are seen around the margin of the shelf. These are areas where the ice is grounded, not areas of marine ice accretion, and they approximate the grounding line location.

This distribution of marine ice beneath the AIS illustrates only part of the complex processes of melting and refreezing that occur under the shelf. Melt rates of tens of metres per year occur at depths of several kilometres near the grounding zone and, from mass flux measurements, as much as 50% of the ice flowing from the interior ice sheet is lost as basal melt. Some of this melt is subsequently frozen back on as marine ice under shallower parts of the shelf. The general features of the melting and freezing under the Amery are reproduced in numerical models of ocean circulation in the cavity (e.g. Williams et al., 1998) as discussed below in Section 4.

From interferometric analysis of RADARSAT SAR data, Young and Hyland (2002) generated a dense network of surface velocity vectors over the AIS (Figure 3). Ice speeds decrease downstream from about 800 m a^{-1} near the confluence of major ice streams at the (redefined) grounding zone to less than 350 m a^{-1} near T4. They then increase to nearly 1400 m a^{-1} at the centre of the calving front. Young and Hyland (2002) derived the strain rate fields over the AIS from these velocities. The distribution of transverse shear strain rates delineate the location of shear margins along the boundaries between flow-bands from different ice streams, and exhibit differences in the flow regime between the southern and northern parts of the shelf.

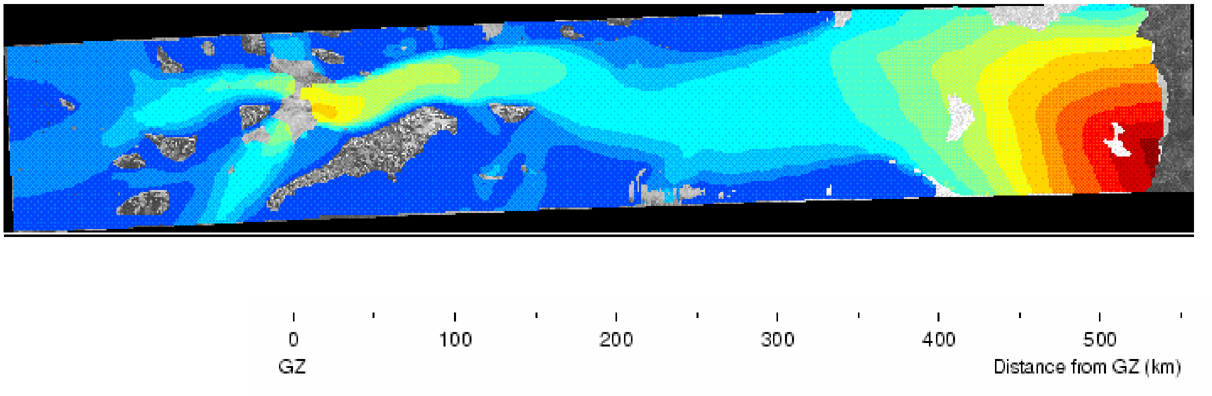

Figure 3 Smoothed distribution of ice speed over the AIS derived from interferometric analysis of LANDSAT SAR data [Young and Hyland, 2002]. The speed scale is linear, varying from less than 100 m a^{-1} (dark blue) to nearly 1400 m a^{-1} at the calving front (dark red).

A gigantic iceberg of about 10,000 km^2 area broke from the AIS at the last major calving event in 1963-64. Fricker at al. (2002b) show from RADARSAT imagery that the front is currently advancing at about 1300 m a^{-1}, but that it will take another 20-25 years to reach its 1963 pre-calving position. However the RADARSAT images also show two major longitudinal rifts in the front of the shelf plus a rapidly extending lateral rift that, when it connects the longitudinal rifts, will calve a 25 km x 25 km iceberg. This will form a bay in the front of the shelf between flow bands originating from the major southern tributaries to the AIS and those originating from more northerly west-side tributaries. Field studies of the processes of propagation of this rift are proposed for the 2002-03 season (Richard Coleman and Helen Fricker; personal communication).

3. The AMISOR project

The importance of processes of ice shelf-ocean interaction to both the Antarctic mass budget and to modification of the characteristics of the ocean, and the sensitivity of these processes to change in ocean temperature or circulation near Antarctica, led to the establishment in 2000 of a project of “Amery Ice Shelf Ocean Research (AMISOR)”. This multidisciplinary project has overall aims of quantifying the interaction between the ocean and the Amery Ice shelf; determining the implications of this interaction for the discharge of grounded ice and to water mass modification; and deriving a long term record (from sediment and ice cores) of the time variability of the interaction. It builds on previous glaciological investigations of the Amery Ice Shelf-Lambert Glacier drainage basin, and of the Prydz Bay oceanography and sedimentary record. The project includes components of hot-water drilling through the AIS to make measurements in the underlying cavity; glaciological measurements of the ice shelf velocity, strain and thickness; oceanographic measurements in Prydz Bay; investigation of sub ice shelf sediments and sediment dynamics; remote sensing; and numerical modelling of ice shelf-ocean interaction and ice shelf dynamics.

The AMISOR field work has both an oceanographic component and a land component. The land component of AMISOR includes *in-situ* measurements of the processes beneath the shelf through a series of access holes drilled completely through the ice. The hot-water drilling program, discussed in detail by Craven et al. (this volume), has successfully drilled access holes through the shelf in January 2001 (370 m depth) and January 2002 (480 m depth). Measurements were made in the ocean beneath the shelf through both holes, and instruments were left in place to continue measurements over several years. These data, combined with the oceanographic data from the front of the shelf, will provide estimates of the amount and distribution of melting and freezing under the Amery. They will also be used to validate numerical models of the ocean circulation in the cavity.

Wong et al. (1998) used 1992 oceanographic data from Prydz Bay to estimate the large-scale impact of processes beneath the ice shelf on water mass characteristics. They showed that there was significant cooling and freshening of the water that flowed beneath the AIS and from this they derived a net melt rate from the bottom of the AIS of between 10.7 Gt a^{-1} and 21.9 Gt a^{-1}. This estimate is very sensitive to spatial aliasing due to the small number of 1992 CTD casts across the ice shelf front, and a much more thorough hydrographic survey was undertaken from *Aurora Australis* within the AMISOR framework in February 2001, and repeated in February 2002.

The scope of the AMISOR oceanographic survey is shown in Figure 4. Top-to-bottom casts for temperature, salinity, oxygen and nutrients were made at 24 stations along the front of the ice shelf in both seasons. Current profiles to 450 m depth were measured with ADCP, and samples were also collected for helium, tritium and oxygen isotope analysis. Preliminary analysis of these data (Nathan Bindoff and Matthew Shanahan; personal communication) shows a strong outflow of Ice Shelf Water in four cores at a depth of 150 m to 400 m, and a total overturning circulation of approximately 1.3 Sv. To determine the seasonal evolution of the circulation under the shelf, seven mooring arrays with temperature, salinity and current sensors were deployed across the front of the shelf in February 2001. These were all recovered in February 2002.

4. Modelling the Amery Ice Shelf

Williams et al (2001) used an ocean circulation model based on that of Determan and Gerdes (1994) to simulate the ocean cavity beneath Amery Ice Shelf. They showed that the sub-shelf circulation was predominantly barotropic, is steered by the cavity topography, and is strongly influenced by melting and freezing processes at the ice-ocean interface. Two different model runs both forced by observations of temperature and salinity near the ice front, with a specified barotropic exchange at the ice front and with no barotropic exchange at the ice front, gave net melt rates of 18.0 Gt a^{-1} and 5.8 Gt a^{-1} respectively. Both models showed basal freezing of several Gt a^{-1}, sufficient to provide substantial layers of accreted ice.

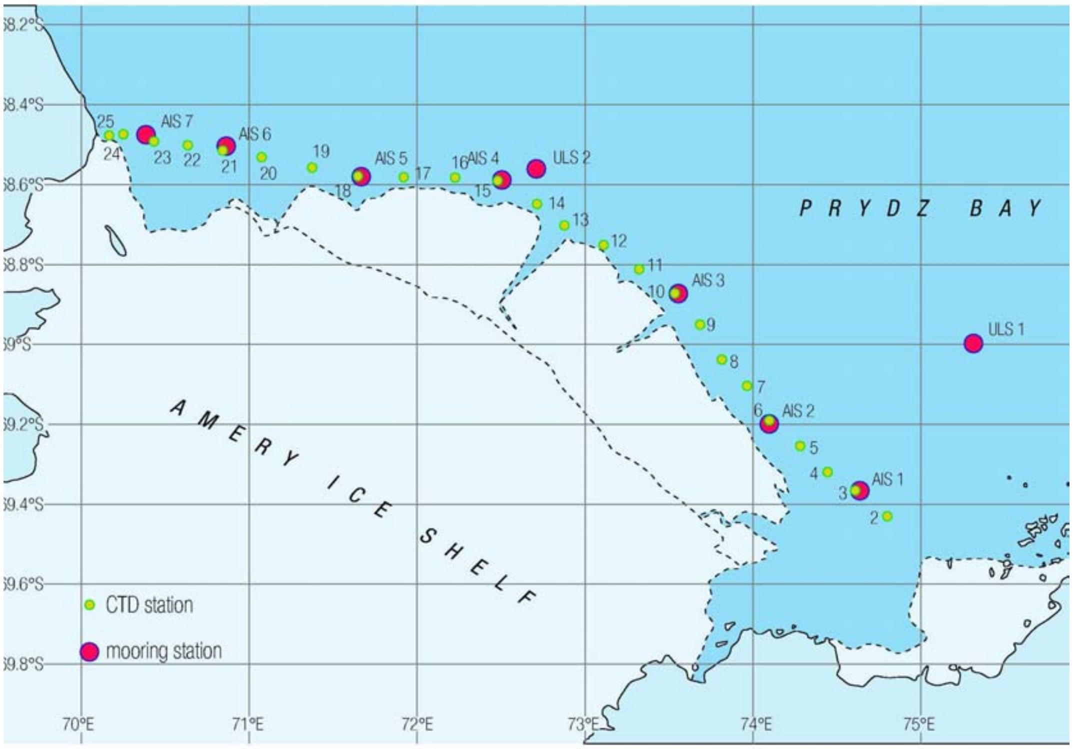

Figure 4 The AMISOR hydrographic survey. Top-to-bottom CTD casts were made at the yellow stations, and seven moorings were deployed at the red stations for one year.

Williams et al. (2002) discuss projections of changes in the climate of the Southern Ocean expected from global climate warming, suggesting that 2°C warming may be expected at depths that influence the ice shelf cavity by the end of the present century. Accordingly, the sensitivity of the ice shelf to ocean temperature increases of up to 3°C was investigated using the same model (Williams et al., 2002), but with a more sophisticated coupling of fluxes of heat and salt at the ice-ocean interface (based on Holland and Jenkins, 1999) and assuming the same barotropic exchange of approximately 0.7 Sv at the ice front. The net mass loss by basal melt doubled, from a new estimate of 14.2 Gt a^{-1} for present net melt, for a 0.5°C temperature increase. This model also showed less present accretion of basal ice than the earlier study. The overall sensitivity from the series of warming simulations was 28.4 Gt a^{-1} K^{-1}. The maximum melt rates increased by as much as 10 m a^{-1} K^{-1}. The consequences of such increased melt would be substantial changes in the ice shelf geometry and dynamics, particularly at the grounding line and ice front. Studies were also made with a version of the model which included the adjacent open ocean but these simulations did not provide a close enough match to the observed water masses adjacent to the ice front to be regarded as suitable for studies of present or future studies of the sub-ice circulation.

To avoid the artificial prescription of the boundary conditions along the front of the shelf, the Princeton Ocean Model (POM), which is the most widely used "coastal" three-dimensional model, has been modernised and adapted to the study of the circulation from Prydz Bay into the cavity beneath the AIS (John Hunter and Mark Hemer; personal communication). An advantage of POM is the inclusion of tides, which may be an important factor in the turbulent exchange of heat with the ice shelf base, and the model is also being modified to include frazil ice. The horizontal extent of the cavity used in the POM runs is that defined by the grounding zone definition of Fricker at al. (2002) (Williams et al used a more northerly grounding line in all their model runs), but the lack of sea-floor bathymetry for the southern part of the Amery cavity remains a deficiency in defining the model domain. A project to compare the two models is being developed (involving Hunter, Hemer, Williams and Warner).

Work has also been undertaken on the development of a dynamic-thermodynamic ice-shelf model (Roland Warner; personal communication). This model has been generalised to incorporate a spatially variable ice flow parameter, enabling incorporation of a treatment of anisotropic ice flow enhancement. Given the strong basal melting and regional basal refreezing observed beneath the AIS, temperature dependent flow rates and enhancement from development of anisotropic crystal fabrics in the bands of sustained high shear may both be important influences on shelf dynamics. Ice velocities obtained from SAR interferometry (Young and Hyland, 2002) have been used with the ice-shelf model equations to infer the spatial pattern of the effective viscosity of the ice of the AIS using control theory methods (Roland Warner, Neal Young and Marty Ross; personal communication), providing a probe of ice flow properties under the low temperatures and stresses, and high strains, applicable to polar ice masses in general.

5. Future directions

Future field work on the AIS (subject to proposal approval and logistic support) will include drilling further access holes to measure ice shelf and ocean cavity properties; to take ice, ocean and sediment samples; and to deploy long-term *in-situ* instruments. The proposed drilling and measurement site for 2003-04 is AM03: 69° 11.1’ S, 70° 17.8’ E. This is a location where substantial basal freezing is predicted. Subsequent field programs will work southward down the centre line of the ice shelf into increasingly thick ice. At all sites the ocean characteristics will be profiled with CTD and acoustic current instruments

In 2002-03, a GPS survey will be undertaken to assess the performance of the GLAS laser altimeter over the Amery Ice Shelf. The project will involve making a series of static and kinematic GPS measurements of the Amery ice-sheet topography along both descending (approximately parallel to the axis of the AIS) and ascending 8-day tracks of ICESat across the AIS. These will be made near-simultaneously (within 8-16 days) with the satellite measurements, and will be used to assess the error budgets of the GLAS altimeter.

To determine the mechanics of ice shelf rift formation and propagation, with the eventual aim of predicting future iceberg calving events, the propagation (widening, elongation and vertical displacement) of the rifts in the front of the AIS will be measured with GPS across a small network of sites for a period of 3 years. Strain rates over a larger area network on the ice shelf will be obtained from GPS measurements and RADARSAT imagery, and used to determine the glaciological force regime. The vertical displacement of the ice shelf across the rifts in response to atmospheric and oceanic (tidal and storm surge) forcing will also be monitored.

Integration of an ice shelf model with ocean circulation and ice sheet models is planned, and work is underway (Petra Heil, Hunter and Warner) in coupling the dynamics and thermodynamics of the ice shelf and ocean models. This will involve further application and development of ocean dynamics models describing the thermohaline circulation beneath floating ice shelves, their interaction with the adjacent open ocean and their coupling to a new model of the dynamics and thermodynamics of the ice shelf itself. This coupled system will be used to study the interaction between the ice shelf and the ocean, and hence with the global climate system. Any substantial change in the geometry of the embayed ice shelves may have consequences for the dynamics of the adjacent grounded ice sheet and hence on the Antarctic mass balance.

A major deficiency for modelling the circulation in the cavity beneath the AIS is the lack of good data on the shape of the cavity. While there are comprehensive data on ice thickness, there are only a few early (Russian) seismic data on the depth of the ocean floor, and very few data at all from the southernmost part of the shelf towards the grounding zone. A seismic survey of the northern region is planned for the 2002-03 season, and further seismic measurements will be taken in future years.

Acknowledgement

This paper aims only to provide a very brief overview of past and present Australian research on the AIS. This is the work, over nearly 50 years, of a considerable number of investigators. The reader is urged to refer to the cited references for details of their work.

References

Allison, I.F. 1979. The mass budget of the Lambert Glacier drainage basin, Antarctica. J.Glaciol., **22**(87),223-235.

Budd, W.F. 1966. The dynamics of the Amery Ice Shelf. J.Glaciol., **6**(45):335-358

Budd, W.F., I.H. Landon-Smith and E. Wishart. 1967. The Amery Ice Shelf. In: H. Oura (Ed.). Physics of Snow and Ice. Proceedings of the International Conference on Low Temperature Science, 1966, 447-467. Institute of Low Temperature Science, Sapporo.

Budd, W.F., M.J. Corry and T.H. Jacka. 1982. Results from the Amery Ice Shelf project. Annals of Glaciology **3**, 36-41.

Craven, M., M. Higham and A. Brocklesby. 2001. Ice thickness and surface & bedrock elevations from the Lambert Glacier Basin traverses 1990-1995. Antarctic CRC Research Report No.23, 76 pp. Cooperative Research Centre for Antarctica and the Southern Ocean, University of Tasmania, Hobart.

Craven, M., Alan Elcheikh, Russell Brand and Ian Allison (this volume). Hot water drilling on the Amery Ice Shelf, East Antarctica.

Determan, J. and R. Gerdes. 1994. Melting and freezing beneath ice shelves: implications from a three-dimensional ocean-circulation model. Annals of Glaciology, **20**, 413-419.

Fricker, H.A., Hyland, G., Coleman, R., Young, N.W. 2000. Digital Elevation Models for the Lambert Glacier - Amery Ice Shelf system, East Antarctica, from ERS-1 satellite radar altimetry. J.Glaciol., **46** (155), 553-560.

Fricker, H.A., S. Popov, I. Allison and N.W. Young. 2001. Distribution of marine ice at the base of the Amery Ice Shelf, East Antarctica, from satellite and airborne measurements. Geophysical Research Letters, **28**(11), 2241-2244.

Fricker, Helen A., Ian Allison, Mike Craven, Glenn Hyland, Andrew Ruddell, Neal Young, Richard Coleman, Matt King, Kim Krebs and Sergey Popov. 2002a. Redefinition of the Amery Ice Shelf, East Antarctica, grounding zone. J. Geophys. Res., **107**(B5), ECV 1/1-1/9.

Fricker, H.A., Young, N.W., Allison, I. and Coleman, R. 2002b. Iceberg calving from the Amery Ice Shelf, East Antarctica. Annals of Glaciology, **34**, 241-246.

Higham, M. and M. Craven. 1997. Surface mass balance and snow surface properties from the Lambert Glacier basin traverses 1990-1994. Antarctic CRC Research Report. No 9, 129pp. Cooperative Research Centre for Antarctica and the Southern Ocean, University of Tasmania, Hobart.

Holland, D.M. and A. Jenkins. 1999. Modelling thermodynamic ice-ocean interactions at the base of an ice shelf. J. Phys. Oceanogr., **29**, 1787-1800.

Kiernan, R. 2001. Ice sheet surface velocities along the Lambert Glacier Basin traverse route. Antarctic CRC Research Report No.23, 76 pp. Cooperative Research Centre for Antarctica and the Southern Ocean, University of Tasmania, Hobart.

Manson, R., Coleman, R., Morgan, P.J., and King, M.A. 2000. Ice velocities of the Lambert Glacier from static GPS observations. Earth, Planets and Space, **52** (11), 1031-1036.

Mellor, M. and G.W. McKinnon. 1960. The Amery Ice Shelf and its hinterland. Polar Record 10(64):30-35.

Morgan, V.I. 1972. Oxygen isotope evidence for bottom freezing on the Amery Ice Shelf. Nature **238**(5364):393-394.

Phillips, H.A., I. Allison, R. Coleman, G. Hyland, P.J. Morgan and N.W. Young. 1998. Comparison of ERS satellite radar altimeter heights with GPS-derived heights on the Amery Ice Shelf, East Antarctica. Annals of Glaciology **27**, 19-24.

Wakahama, G. and W.F. Budd. 1976. Formation of the three-layered structure of the Amery Ice Shelf, Antarctica. J.Glaciol., **16**(74):295-297.

Warren, S.G., Roesler, C.S., Morgan, V.I., Brandt, R.E., Goodwin, I.D. and Allison, I. (1993) Green icebergs formed by freezing of organic-rich seawater to the base of Antarctic ice shelves. *J* J. Geophys. Res., **98**, 6921-6928

Williams, M.J.M., R.C. Warner and W.F. Budd. 1998. The effects of ocean warming on melting and ocean circulation under the Amery Ice Shelf, East Antarctica. Annals of Glaciology **27**, 75-80.

Williams, M.J.M., Grosfeld, K., Warner, R.C., Gerdes, R., and Determann, J. 2001. Ocean circulation and ice-ocean interaction beneath the Amery Ice Shelf, Antarctica. J. Geophys. Res., **106** (22), C10, 383-399.

Williams, M.J.M., Warner, R.C., and Budd, W.F. (2002). Sensitivity of the Amery Ice Shelf, Antarctica, to changes in the climate of the Southern Ocean. J. Climate, **15**, 2740-2757

Wong, A.P.S., N.L. Bindoff and A. Forbes. 1998. Ocean-ice shelf interaction and possible bottom water formation in Prydz Bay, Antarctica. In: Ocean, Ice and Atmosphere: Interactions at the Continental Margins, American Geophysical Union Antarctic Research Series 75, edited by S.S. Jacobs and R.F. Weiss, pp. 173-187, AGU, Washington D. C.

Young, N.W. and G. Hyland. 2002. Velocity and strain rates derived from InSAR analysis over the Lambert Glacier - Amery Ice Shelf system. Annals of Glaciology, **34**, 228-234.