Antarctic tabular iceberg evolution during northward drift: A proxy system for studying ice shelf break-up

T. Scambos,[1] J. Bohlander,[1] T. Haran,[1] R. Ross,[2] and R. Bauer[1]

[1]National Snow and Ice Data Center, University of Colorado, 1540 30th Street, Boulder, CO 80309, USA (teds@nsidc.org)
[2]Avega Systems, 59 Victoria Street, McMahons Point, Sydney, Australia (r.ross@thistle.org)

Abstract Drifting tabular icebergs in the Southern Ocean just east of the Antarctic Peninsula undergo a rapid 'climate change' as they move into warmer air and ocean temperatures. Using a combination of satellite sensors and satellite-uplinked automated observing stations on two bergs during 2006-2007, we examine these changes for clues to ice shelf and ice tongue break-up processes. Icebergs evolve slowly while south of the sea ice edge, but undergo rapid changes as they move north towards South Georgia Island. Surface melt and firn compaction dominate the early evolution (inferred from automated photos of accumulation stakes) but basal melting steadily increases. Edge-wasting of icebergs in warm (sea-ice-free) water suggests a mechanism for ice tongue retreat in the absence of firn saturation and melt ponding. However, in several cases we have observed that rapid calving begins once the firn is saturated with water, and surface or near-surface ponding occurs.

Citation: Scambos, T., J. Bohlander, T. Haran, R. Ross, and R. Bauer (2007), Antarctic tabular iceberg evolution during northward drift: A proxy system for studying ice shelf break-up: *in* Antarctica: A Keystone in a Changing World – Online Proceedings of the 10th ISAES, edited by A.K. Cooper and C.R. Raymond et al., USGS Open-File Report 2007-1047, Extended Abstract 157, 6 p.

Introduction

Our study reports on the drift, surface physical characteristics, satellite observations, and evolution of 2 large tabular icebergs derived from the Ronne Ice Shelf front and southern Larsen C Ice Shelf (Figure 1) that drifted north into the region of South Georgia Island. The icebergs are A22A, initially 60 by 40 km in size, and the UK211 iceberg, initially 12 by 10 km, which we have informally named 'Amigosberg'. We supplement our analysis of these two icebergs with additional remote sensing data from four other icebergs, described in Scambos et al., 2005. Our study incorporates remote sensing data from satellite images, satellite laser altimetry, radar scatterometry, and aerial observations and field data from two field visits to the former two icebergs and two automated observation systems installed on these bergs during the field work.

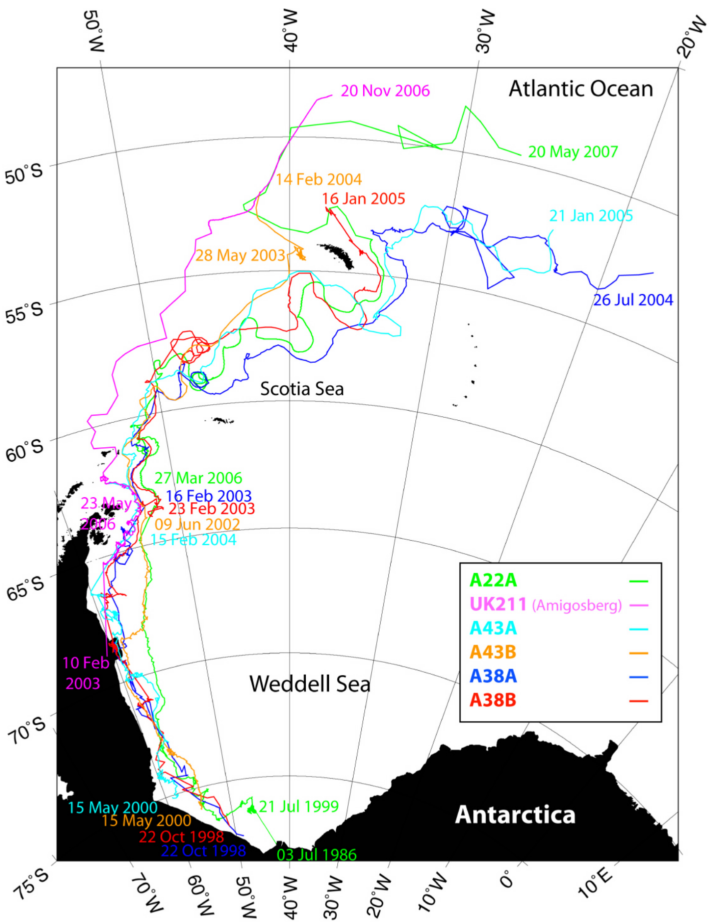
The objective of the study is to evaluate the degree to which icebergs can inform models or hypotheses of ice shelf disintegration due to climate change. As they drift, icebergs experience a rapidly-changing environment. In the Antarctic Peninsula to South Georgia Island region, this change is in the direction of rapid warming of both air and sea temperature, and increased exposure to ocean swell.

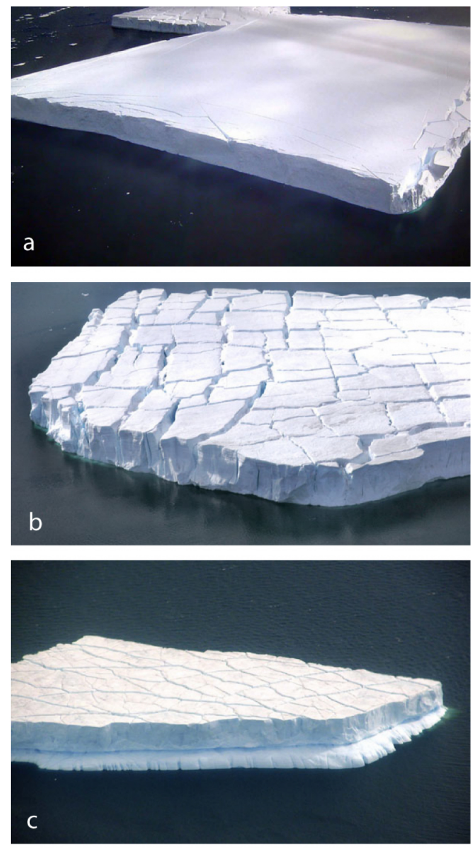
Methods

Satellite images of the icebergs consisted of a series of scenes from the Moderate-Resolution Imaging Spectro-Radiometer (MODIS) using the red-light and infrared Band 1 and Band 2 channels (650 and 870 nm) with a nominal resolution of 250 m. These images provided information on iceberg location, iceberg area, calving events and changes in surface character. Images with sufficient visibility to provide position and shape data were available every two to three days on average for the periods of greatest interest. Many of the clearer images are archived at the ice shelf monitoring site at National Snow and Ice Data Center (NSIDC; http://nsidc.org/data/iceshelves_images/). The scenes in this archive are gridded to polar sterographic and Lambert Conformal Conic projections using the NSIDC software tool MS2GT (Haran, 2002), and then digitized to determine area. Iceberg locations are provided by the Antarctic Iceberg Tracking Database using QuikSCAT scatterometry data, (http://www.scp.byu.edu/data/iceberg) supplemented by in situ GPS data from automated berg observing stations. Additional data on iceberg movement, based on numerous satellite sources, is available from the National Ice Center (http://www.natice.noaa.gov). Elevation (freeboard) data for the A22A iceberg comes from the Ice, Cloud and land Elevation Satellite (ICESat), which acquires profiles of precise (+/- 20 cm) elevations in spots of ~70 m diameter spaced 172 m apart.

Additional observational data were acquired during overflights of numerous icebergs near the Argentine Antarctic base Marambio, and from the Argentine Navy icebreaker ARA *Almirante Irizar*. Low-level surveys of ice edges were conducted to observe and photograph (Figure 2) fracturing, edge character, melt layering, and approximate freeboard height prior to landings on three icebergs (Amigosberg, A22a, and an unnamed small iceberg just east of Marambio).

During brief (~20 hour) field visits to Amigosberg and A22a, we installed two automated data collection systems, which we call Automated Met-Ice-Geophysics Observation Stations (AMIGOS; Figure 3). The units consist of a Linux-CPU board and mini-network system, with an Iridium digital satellite telephone uplink. The system is powered by rechargeable 80 to 100 amp-hour batteries (3 or 4) and 2 or 3 of 10 to 20 watt solar panels. Instruments for scientific measurement include a CA code Global Positioning System (GPS) receiver (~3 meters precision, latitude and longitude only), air temperature thermometer, a steerable digital camera, and on one of the stations, an ice thickness measurement system based on a simple radio echo sounder. Quantitative measurements were accomplished with the camera by placing lines of flags from the camera towards the ice edge, for detection of edge wasting rates and ice edge flexure (see Scambos et al., 2005), and installing accumulation/ ablation stakes near the station (Figure 3b).





Figures 1 and 2. Figure 1 (left) is a map of the drift tracks of the main large icebergs studied here. Figure 2 (trio on right) shows the surface and edge characteristics of several small icebergs near Marambio station.

Observations

Iceberg movement: QuikSCAT, MODIS, and GPS tracking

Figure 1 illustrates the movement of the icebergs, combining ~twice weekly QuikSCAT and MODIS image locations with hourly GPS positions for the two icebergs carrying AMIGOS systems during the period of their operation. As has been noted by numerous previous studies (Wordie and Kemp, 1944; Swithinbank et al., 1977; Ferrigno and Gould, 1987), the general trend of motion in the Weddell Sea – Scotia Sea – South Georgia Island region is a clockwise crescentic drift, closely following the eastern continental shelf edge of the Antarctic Peninsula, and then proceeding northeastward towards South Georgia Island. Large bergs generally track north of Orcadas Island, and most pass south of South Georgia Island, although two of the six studied here proceeded to the west of the island (A43B and Amigosberg).

The iceberg tracks of the six bergs show repetitive patterns, and several of these bergs have nearly overlapping drift tracks for distances of hundreds of kilometers. In the vicinity of the eastern Peninsula continental shelf, the repetition is likely due to interaction with shoals, with driving currents that are generally more westerly-trending than the shoal isobaths. If so, it is possible that the iceberg drift tracks are separated on the basis of iceberg thickness, with thicker iceberg tracks similar to, but eastward of, those of the thinner bergs. Amigosberg, derived from the southern Larsen C shelf, and likely the thinnest iceberg of the study group, drifted considerably west of the rest in the Bransfield Strait region, and proceeded between Elephant Island and Clarence Island an then well to the west of South Georgia on a more north-northeasterly track. Another repetitive pattern, with differences likely due to iceberg thickness, is interaction with east-west-trending shoals along the eastern Peninsula shelf. Ocean current controls on the icebergs also appear to be highly repetitive, e.g., in the region north of Orcadas Island (large gyre-like motion, ~100km diameter 'orbits'), and in the area east and north of South Georgia. Note that three of the studied bergs, Amigosberg, A43B, and A22a, all drift along the same narrow path near 52°S, 43°W.

Calving styles and edge-wasting rates – MODIS satellite images

A series of images of the two field-studied icebergs, A22A and Amigosberg, provide a record of the pace of edge calvings and iceberg area with position (Figure 4). Using ~35 images for each iceberg, spanning the period of drift from sea-ice-covered areas to the region north of South Georgia Island, we measured area and iceberg perimeter length from projected imagery. The image series shows that icebergs lose very little area in cold-water (sea-ice-covered) environment, but begin to lose mass as soon as they encounter open water. This mass temperature). However, for Amigosberg, in situ loss increases with northward drift (and therefore ocean observations provide evidence for water saturation in the firn in the late stages of its decay (see below). Rates of area loss accelerated considerably after this date.

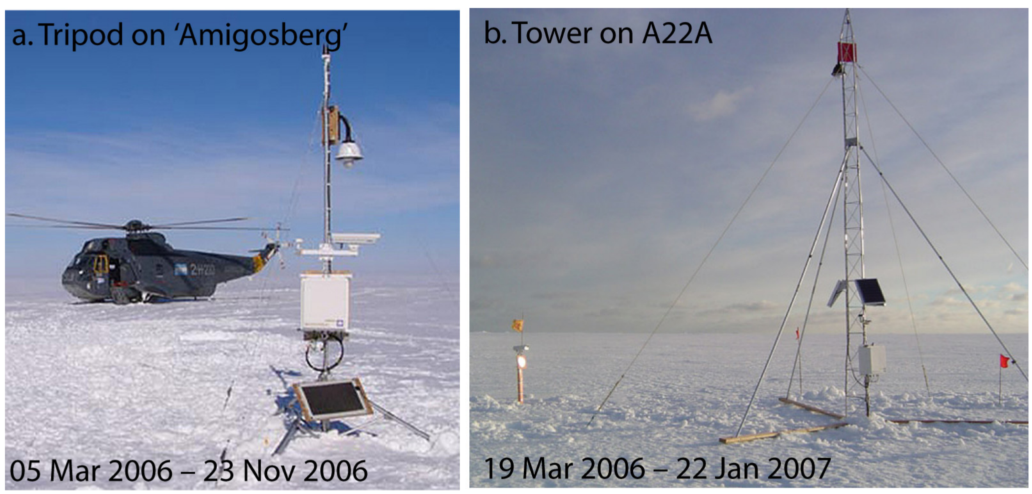


Figure 3. The Automated Met-Ice-Geophysics Observation stations (AMIGOS) installed on the two primary study icebergs, and their periods of operation. Note orange accumulation/ablation post on the left in 3b.

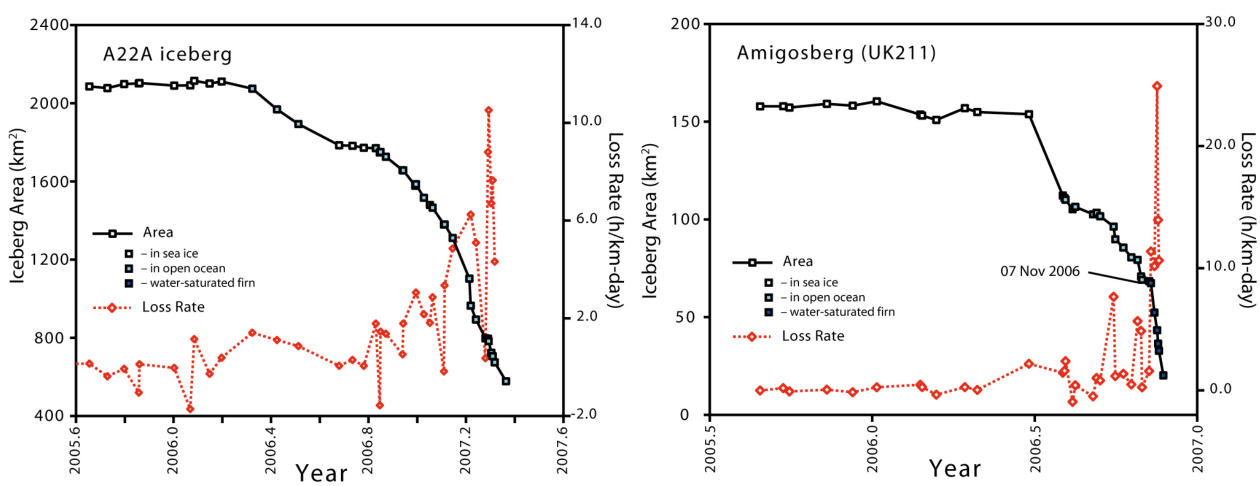


Figure 4. Area loss and edge-wasting rates during the northward drift for A22A and Amigosberg. Units for the loss rate (right axis of both graphs) are hectares per kilometer of iceberg perimeter per day. Note pause in rate of loss for A22A as winter sea ice extent enveloped the iceberg; note also rate increase after November 7, 2006, when in situ photographs of a firn pit showed evidence of water-saturated firn (see Figure 7).

Iceberg edge and surface structures – Aerial photography, ground observations

As part of the field preparation and field expedition landings, we carefully examined the edges and surface of the icebergs Amigosberg, A22a, and numerous smaller icebergs near Marambio station. A sample of aerial photographs is given in Figure 2. In general, all icebergs smaller than ~3 km across showed evidence of flexure, presumably by long-period ocean swell (lesser and greater degrees of fracture are shown in Figure 2 a and b). However, larger icebergs in general had un-fractured interiors (at the scale of visible observation from aircraft), and were only fractured within a few hundred meters of their edges. Waterline patterns in sea-ice-covered regions were near-vertical; but in areas north of the sea ice edge, a distinct 'bench' was observed (Figure 2c), indicating that waterline erosion is rapid, and can flex or tilt iceberg edges (Scambos et al., 2005)

Ice thickness changes – ICESat freeboard data

Three profiles from separate ICESat data acquisition periods, from November 4, 2004, March 13, 2006, and November 10, 2006, provide near-repeat elevation information across the same region of the A22A iceberg (see Figure 5; this is a remarkable coincidence considering drift and rotation of the iceberg, and spacing of ICESat tracks). Earlier analysis of the A38A and A38B icebergs indicated that little basal melting (~1 meters freeboard change per year) occurs on the bergs while in the Weddell Sea, and this conclusion is generally supported here. Ice losses over the 18 month period, during which time the iceberg drifted from near the Ronne Ice Shelf front to the edge of the sea ice, averaged ~3 meters freeboard loss. In the following 8 months, the iceberg lost 7.5 additional meters of freeboard.

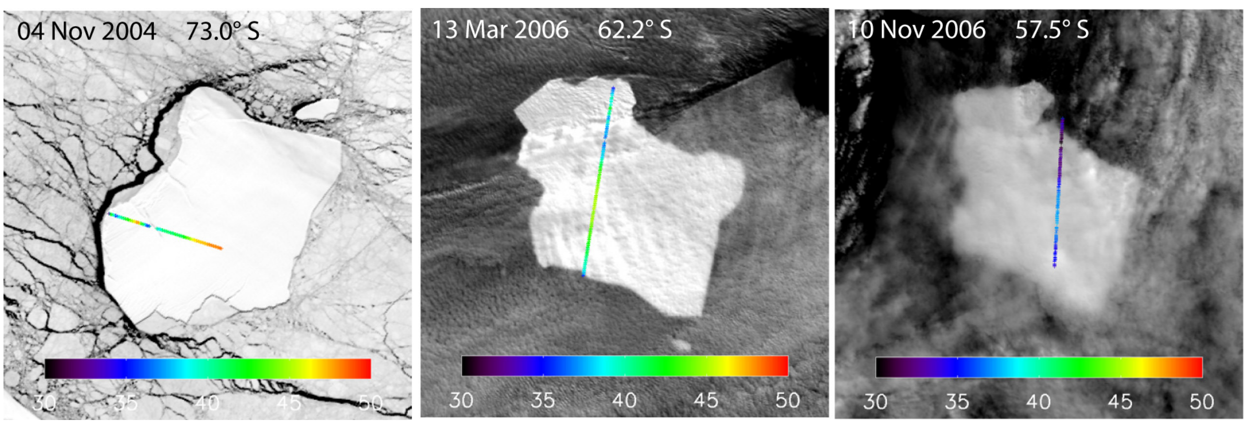


Figure 5. MODIS images with color-coded elevations (freeboards) derived from ICESat data for A22A.

Observations during field work and from In Situ AMIGOS units

Uplinked images from the AMIGOS units provide a unique data set on iceberg firn processes during drift into warmer conditions. By recording snow levels on several poles and masts placed within the field of view of the steerable camera, we are able to record accumulation and ablation rates of the two icebergs (green line, Figure 6). We compare these results with the ~1m air temperature recorded by the station (red line) and extract a degree-hours plot as well (blue line). Both icebergs showed initial accumulation, but then up to one meter of ablation during the period of good camera observations. Extrapolating to the late stages of iceberg decay, we estimate that 2 to 3 meters of surface snow are melted and refrozen into the underlying firn by the late stages of iceberg breakup. This implies a significant firn densification, and impacts the estimate of thinning based on freeboard, discussed above.

An important result from the Amigosberg AMIGOS unit is the observation of ponded water just below the firn surface in the days just prior to an increase in rate of breakup. In Figure 7, we show four images of a pit formed around the batteries during the ablation period (the system is directed to image the unit footpads, solar panels, batteries, and adjacent firn every day) In the image sequence, one can see white firn on November 2 and 3, some pale bluish tint on November 5, and clear evidence of meltwater in the pit on November 7.

Discussion and conclusions

Rapid northward drift of large tabular icebergs causes them to encounter rapidly changing air and ocean water appears to be linked to iceberg size, and therefore may depend on the wavelength of the ocean current. Given the effects on ~1 – 2km bergs noted and illustrated above, it is worth investigating whether smaller effects may occur on larger icebergs, or, more importantly, on ice shelves with exposure to ocean swell. The effect of swell has been implicated in a very large iceberg breakup in the Ross Sea region (MacAyeal et al., 2006).

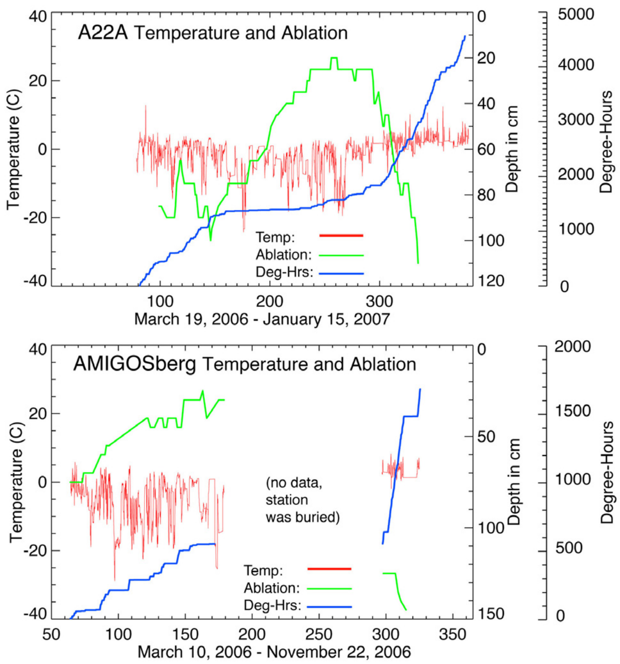


Figure 6. Air temperature, accumulation-ablation, and cumulative degree-hours from AMIGOS units.

The observation of waterline erosion, the formation of 'benches', and the onset of significant edge-wasting of icebergs only after drifting into ice-free, above-freezing water implies that waterline erosion may play a significant role in ice shelf or ice tongue retreat. In this scenario, loss of a sea-ice cover leads to warming of surface water. Waterline erosion causes above-waterline spalling, leaving a below-waterline 'bench' of ice that begins to stress the ice plate. Scambosb et al. (2005) conditions that in some ways mimic what transpires around ice shelves in warming climate

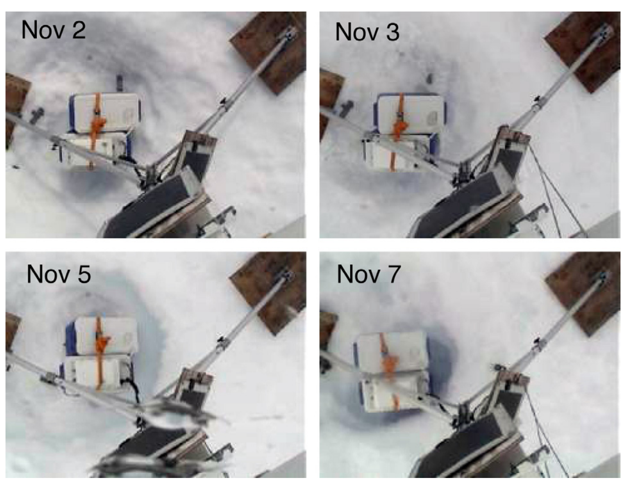


Figure 7. AMIGOS camera image sequence of firn pit on Amigosberg. Note blue patch to right of battery cases on November 5 (very pale) and November 7 (darker).

conditions. Large-scale drift of icebergs (i.e. excluding tides, which cause oscillatory motion during drift) shows remarkable repeatability, not only where bergs interact with the seafloor, but also in regions of persistent gyres or convergent currents. Icebergs are significantly flexed by ocean swell, but the degree to which this can induce large-scale fracturing noted the 'rampart-and-moat' edge profile from ICESat data due to this flexing. As the bench increases, stress builds until bottom calving releases a secondary iceberg, causing the main berg (or ice tongue, or ice shelf) to gradually shrink in area. Basal melt of icebergs increases rapidly with northward drift, as inferred from freeboard measurements. However, a significant fraction of this freeboard reduction, between 2 – 3 meters in the bergs studied here, can be due to firn densification from surface melt and percolation, in the latest stages of decay. Nevertheless, thinning rates increase rapidly as the berg transitions from Weddell Sea to Scotia Sea and southern South Atlantic water. It is still unclear if a critical minimum iceberg thickness (or minimum shelf thickness) is a factor in iceberg/ice shelf disintegration (e.g., Shepherd et al., 2003).

However, this study strongly supports the theory that accumulated meltwater on an iceberg surface (or ice shelf or ice tongue surface), or stored water within porous firn, has a major effect on iceberg/ice shelf stability. The effect of this water is presumably increased fracture penetration, as outlined in Weertman, 1973, Scambos et al, 2003, and Van der Veen, 2007. Rates of edge wasting increased by nearly an order of magnitude on Amigosberg after the observation of saturated firn. A similar large increase in calving rate was observed for A43B after ponds were imaged on its surface (Scambos et al., 2005) and for A43A after a distinct bluish tint was observed in MODIS images. For A22A, firn may be nearing the water-saturated state as of this writing (31 May, 2007).

Acknowledgements. We thank Yevgeny Yermolin, Juan Carlos Quinteros, Ing. Pedro Skvarca, and Dr. Rudolfo Del Valle of Argentina, and Jonathan Thom of University of Wisconsin, United States for their outstanding assistance during the field visits to the icebergs from Marambio Station and the ARA *Almirante Irizar* in February and March of 2006; our thanks extend to the excellent military and civilian staff of Marambio and *Irizar* as well, in particular the pilots and meteorological personnel. Dr. Douglas MacAyeal provided inspiration and advice for this work. Dr. Neil Humphrey provided a radio-echo-sounding system for A22A. This work was supported by NSF SGER Grant OPP-0540915 and NASA Grant NNG06GA69G.

References

Ferrigno, J., and W. Gould (1987), Substantial changes in the coastline of Antarctica revealed by satellite imagery, Polar Record, 23(146), 577–583.

Haran, T. M., M. A. Fahnestock, and T. A. Scambos (2002), De-striping of MODIS optical bands for ice sheet mapping and topography. Eos Transaction of the American Geophysical Union*,* 88(47), F317.

MacAyeal, D. R., and 13 others (2006), Transoceanic wave propagation links iceberg calving margins of Antarctica with storms in tropics and Northern Hemisphere. Geophys. Res. Lett., doi: 10.1029/ 2006GL027235.

Scambos, T., C. Hulbe, and M. Fahnestock (2003), Climate-induced ice shelf disintegration in the Antarctic Peninsula. In Antarctic Peninsula Climate Variability; historical and paleoenvironmental perspectives, edited by E. Domack et al., pp. 79-92, AGU, Washington, D.C.

Scambos, T., O. Sergienko, A. Sargent, D. MacAyeal, and J. Fastook (2005), ICESat profiles of tabular iceberg margins and iceberg break-up at low latitudes. Geophys. Res. Lett., doi: 10.1029/ 2005GL023802.

Scambos, T., O. Sergienko, A. Sargent, D. MacAyeal, J. Fastook, and D. Long (2005), Tabular iceberg evolution and break-up at low latitude: imitating ice shelves. Eos Trans. AGU, 86(52), Fall Meet. Suppl., Abstract C13A-02.

Shepherd, A., D. Wingham, T. Payne, and P. Skvarca (2003), Larsen Ice Shelf has progressively thinned. Science, 302, doi: 10.1126/ science.1089768.

Swithinbank, C., P. McClain, and P. Little (1977), Drift tracks of Antarctic icebergs. Polar Record, 18, 495–500.

Van der Veen, C.J. (2007), Fracture propagation as means of rapidly transferring surface meltwater to the base of glaciers. Geophys. Res. Lett. 34, L01501, doi: 10.1029/2006/GL028385.

Vaughan, D. G., and C. S. M. Doake (1996), Recent atmospheric warming and retreat of ice shelves on the Antarctic Peninsula. Nature 379, 328-331.

Weertman, J. (1973), Can a water-filled crevasse reach the bottom surface of a glacier?, Int. Assoc. of Scientific. Hydrology Publication, 95, 139–145.

Wordie, J., and S. Kemp (1944), Observations on certain Antarctic icebergs. The Polar Times, 18, 1–5.