

calculated for smaller glaciers such as Smith, Kohler, DeVicq and Land. SRA observations confirm that the elevation of this sector of the ice sheets is decreasing with time, with thinning larger nearer to the coast and propagating hundreds of km inland. The combination of mass budget and elevation change suggest that this sector of Antarctica is losing enough mass to raise global sea level by 0.2 mm/yr. In addition, SRA reveals that large sectors of ice shelves are thinning rapidly, up to 4 m/yr on Dotson ice shelf. Melting of the ice shelves does not raise sea level, but the ice shelves may exert some control on the ice discharge from the glaciers. If the ice shelves buttress the glaciers, the contribution to sea level rise of this sector of Antarctica may be larger in the future.

C52A MCC: 123 Friday 1330h

Recent Changes in the Antarctic Ice Sheet, Natural Variability, and Global Warming II (joint with A, H, OS, GC, PP)

Presiding: S Tulaczyk, University of California, Santa Cruz; A Shepherd, Scott Polar Research Institute

C52A-01 1335h INVITED

On the sensitivity of the Antarctic Ice Shelves to a Warming Ocean

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The underside of ice streams flowing from the Antarctic continent typically melt into the ocean where they cross the grounding line and begin to float as ice shelves and ice tongues. Melting is governed by the transport of ocean heat and by the seawater freezing point dependence on pressure. The resulting melt water participates in the ventilation of the deepest parts of the ocean. Here, we calculated bottom melt rates of > 25 of the largest glaciers in Antarctica, combining satellite radar interferometry with other data, and compared the results with thermal forcing from the ocean. Melt rates are calculated close to grounding lines of deep-draft glaciers because discharge of continental ice is principally controlled by these glaciers, and because these regions are the locus of high bottom melting. The bottom melt rates range from < 4m/yr to > 40 m/yr. The wide range of values is consistent with limited prior studies, and stems from different grounding line drafts and sea water temperatures. The melting rate is positively correlated with thermal forcing, increasing by 1 meter per year for each 0.1° rise in ocean temperature. Those results have important consequences for modelling studies of the evolution of Antarctica in a warming climate and for the analysis of observations of cryospheric changes from satellites: 1) the inferred rates are much higher than used in modelling studies, which often assume melting to be uniform over the entire ice shelf area, and henceforth underestimate the impact of thermal forcing of the ocean on the ice sheet evolution; 2) the potential impact of bottom melting on short-term ice sheet stability is greatest in regions where deep water has access to glacier grounding lines, e.g. the south-east Pacific-west Antarctic Sector, but also sectors of East Antarctica; 3) Ocean temperature seaward of Antarctica's continental shelf break have risen 0.2° over recent decades, enough to account for the rapid thinning of ice shelves in the western Amundsen sea, which may play an essential role in the observed flow acceleration and mass loss of their nourishing glaciers.

This work was performed at the California Institute of Technology's Jet Propulsion Laboratory and at the University of Columbia, under a contract with the Cryospheric Science Program of the National Aeronautics and Space Administration.

C52A-02 1355h INVITED

Rift formation and growth on the Ross Ice Shelf

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The Antarctic ice sheet sheds much of its mass via the calving of large icebergs. The fronts of the Ross and Filchner-Ronne ice shelves, which produce large tabular icebergs, calved three large icebergs in the year 2000 that, collectively, contained roughly twice the annual accumulation for all of Antarctica. Several other large calving events occurred in 2001-2002, including the dramatic breakup of the Larsen B ice shelf. Located much further south than the Larsen, the Ross and Filchner-Ronne ice shelves are believed to be more stable in that it would take a rise in summer temperatures of several degrees to produce surface meltwater in the quantities that are believed to have contributed to the demise of the Larsen.

Calving events along a given section of the ice front occur decades apart, making it difficult to obtain sufficient observations to statistically separate the natural variability typical of a stable ice shelf from any longer term trend. It thus becomes necessary to better understand the process of tabular iceberg calving to develop the ability to determine whether individual events are normal or signify a response of the ice sheet/shelf system to climate change.

The process of calving from the large ice shelves appears to be driven by the formation and propagation of large-scale ice-shelf rifts that become iceberg detachment boundaries. We have collected interferometric synthetic aperture radar observations (InSAR) of the actively growing rift system on the western side of the Ross Ice Shelf that gave rise to iceberg C19 in May 2002. Our analysis of these data suggests that the rifts open at a steady rate, largely in response to the stresses present in the ice shelf.

C52A-03 1415h INVITED

Explosive break-up of Larsen Ice Shelf, Antarctica, by a meltwater-triggered iceberg capsize mechanism

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Two disintegration events leading to the loss of Larsen A and B ice shelves in 1995 and 2002, respectively, proceeded with extreme rapidity (order several days) and reduced integrated ice shelf to a jumble of small iceberg fragments. These events strongly correlate with warming regional climate and accumulation of surface melt water, supporting the hypothesis that meltwater induced propagation of pre-existing surface crevasses may have started ice-shelf fragmentation. What we address in this study is not the crevasse propagation process that triggers disintegration, but rather a mechanism that may sustain the ice-shelf break-up once it begins. The proposed mechanism involves the coherent capsize of narrow (less than thickness) ice-shelf fragments by rolling 90° in a direction toward the ice front. We envision such fragments as being pieces of ice shelf liberated when two surface or basal crevasses oriented across the pre break-up flow direction suddenly cleave the entire ice thickness, e.g., as a result of meltwater crevasse wedging. Fragment capsize liberates gravitational potential energy and creates forces that wedge open ice-shelf rifts (void space containing the fragment). We speculate that the wedging forces so created may stimulate further fragmentation of the ice shelf and thereby contribute to its sudden disintegration. The process we propose is analogous to the overflow of a champagne bottle that has been opened after having been vigorously shaken. In the analogy, bubbles play the role of ice-shelf voids (rifts) that contain floating ice fragments that can capsize, and CO₂ gas within the bubbles plays the role of capsizing ice fragments that create wedging forces tending to widen the rifts that contain them. Observational support for our proposed mechanism is provided by post-break-up MODIS (visible) satellite imagery that reveals formerly englacial debris exposed at the surface and small, blue-colored sub-pixel-sized icebergs that have rolled onto their sides.

C52A-04 1430h INVITED

Sediment Lithofacies From Beneath the Larsen B Ice Shelf: can we Detect ice Shelf Fluctuation ?

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Cruise 01-07 of the USAP research vessel N. B. Palmer was part of a multi-year investigation of the sediment processes and paleohistory of the Larsen Ice Shelf. Data includes: real-time satellite derived (SEA-WIFS) surface productivity estimates, surface pCO₂, salinity and temperature measurements, surface to bottom CTD measurements, bottom photos, swath bathymetry, and surface grabs, kasten cores and multicores. Observations document the characteristics of the oceanographic and seafloor setting prior to the most recent collapse of the Larsen B system (late February-March of 2002) but following the penultimate retreat (1999). Swath (multibeam) mapping revealed a streamlined seafloor that clearly delineates the former flow path of glacial ice that at one time filled the embayment. A broad trough extends to depths in excess of 700 m in the center of the embayment. This deep extends beneath the edge of the Larsen-B ice shelf as it stood in December-January 2001-2002. A pavement of angular pebbles and cobbles covers the seafloor within the embayment and is underlain by 20 to 60 cm of silty clay, followed by poorly sorted granulated sediment and, finally, a gray diamicton (interpreted as a till). It appears from our preliminary stratigraphy and chronology that the Larsen-B ice shelf has not experienced a history of recession and reformation since the LGM. Instead the ice shelf appears to have been in place for some time while embayment to the north were experiencing open marine conditions (Domack et al., 2001 & Pridemore et al., 2001). This working hypothesis remains to be tested against a growing geochemical and micropaleontological database.

URL: <http://www.hamilton.edu/news/exp/Antarctica2001/>

C52A-05 1450h

Retreating ice shelves on the Antarctic Peninsula

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In recent decades, several ice shelves on the Antarctic Peninsula have retreated, some reduced to fragments of their original size. These retreats have been linked to the rapid recent region atmospheric warming, however, the mechanisms by which small rises in temperature cause retreat are still unclear. Earlier this year, there was a dramatic collapse of Larsen Ice Shelf B, 3250 sq. km of ice shelf were lost in a few weeks. This collapse, was predicted by modelling, as a final-stage dynamic failure following many years of progressive retreat. Less dramatically but no less important, Jones Ice Shelf has also retreated. Although it was stable between 1947 and 1969, retreat began in the early 1970s and continued until 2001, when only a fragment remained. Unusually, Jones Ice Shelf has two ice fronts only a few kilometres apart which provides a unique opportunity to compare how different icefronts retreat when subjected to similar climate forcing. We show that, while particular episodes of retreat may be related to warm summers the overall progress of retreat of the two ice fronts has been controlled by the geometry of their embayments and is substantially different. These observations and a new determination of climate variability on the Antarctic Peninsula allows us to re-define the distribution of retreating and stable ice shelves, and to map a ?limit of viability for ice shelves?. The magnitude of recent rapid regional warming is sufficient to explain the distribution of retreating ice shelves as a result of migration of this limit, and to allow prediction of ice shelves under threat in near future.

C52A-06 1505h

Using an ice-flow model to constrain the cause of the observed thinning of Pine Island Glacier, West Antarctica

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This work aims to determine the cause of the observed thinning of Pine Island Glacier (PIG), West Antarctica. The thinning was detected by repeat satellite altimetry between 1992 and 1999. The measured thinning is at a maximum near the grounding line (3.5 m yr^{-1}), where it is consistent an 8-km retreat of the grounding line, but extends some 150 km up glacier of this (in fact covering most of the area of the main ice stream).

There are three potential causes for this thinning. First, the partial loss of its ice shelf may have led to an acceleration of PIG's flow. Second, internal changes within the ice stream may have affected its flow, most likely changes in basal traction. Third, it could be a response to long-term climate change.

We use a 3d model of the stress and strain regime within an ice mass to determine the effects of various boundary condition changes on the flow of PIG. The numerical model has a full representation of the stress regime except that: the 'bridging' term is omitted (i.e., the model is second order and solves for horizontal velocity alone); and velocity parallel to the main axis of the ice stream is assumed to far exceed that transverse to it (the model solves for one rather than both horizontal components of velocity). Data on the ice thickness and bedrock elevation of PIG are limited to two BAS flight lines. We therefore consider a simplified geometry in our model, which assumes flow in a single rectangular bedrock channel of constant cross-flow depth. The model includes the main trunk of PIG as well as its fringing ice shelf. Zero-velocity boundary conditions are applied to the lateral and up-glacier boundaries of this domain. The boundary condition on the seaward boundary of the ice shelf balances the weight of displaced seawater. We tune the basal boundary conditions so that the predicted ice-surface velocities match those observed using satellite interferometry.

A series of experiments are then performed to assess the consequences of ice-shelf thinning and changing basal traction. Early results imply that the former scenario cannot explain the widespread thinning of the main trunk of PIG.

C52A-07 1520h

West Antarctic Ice Stream Discharge Variability: the evidence, a mechanism, and its implications

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West Antarctic ice streams show pronounced flow variability in their downstream reaches, with changes stranding formerly fast-flowing ice and redirecting discharge. A simple scenario, in which the temperature gradient in basal ice provides control of fast sliding in the downstream reach, can explain this behavior. We develop this conceptual model using observations of the ice flow record and a numerical model of the thermal evolution of Whillans Ice Stream. In brief, as the ice flows downstream, vertical strain causes the temperature gradient in basal ice to steepen, thereby promoting basal freezing and dewatering of the ice/bed interface. Loss of basal meltwater causes ice to slow and discharge is redirected around the obstruction. This process may put an upper bound on the retreat rate and discharge flux of the WAIS ice-stream system under present climate. It also provides a very simple explanation for the large thickness of accreted ice known to exist at the base of at least one ice stream.

C52B MCC: 123 Friday 1600h

Glaciers and Ice Sheets I (joint with A, H, GC, PP)

Presiding: T Murray, University of Leeds; D R MacAyeal, University of Chicago

C52B-01 1600h

An Airborne Radioglaciological Survey of Iceberg B15a on November 23, 2001

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Understanding the migration and disintegration of large tabular icebergs requires knowledge of their thickness and basal character as well as the distribution of vertical fractures originating at both the surface and the base. An efficient method for making these observations is with an airborne ice-penetrating radar. The primary problem with these radar measurements is the large system sensitivity required to observe simultaneously large-amplitude reflections from the ice-ocean interface and the more subtle high-resolution signals from near-surface scatterers and englacial layering.

During the 2001/2002 austral summer, the University of Texas was field testing an experimental radar sounder (developed in collaboration with the Jet Propulsion Laboratory) mounted on a twin-engine aircraft operating from the Ice Runway at McMurdo Station. With this system, which was designed specifically to optimize both resolution and sensitivity, we performed phase-coherent radar imaging along four profiles over iceberg B15a which, at that point in time, was lying nearly perpendicular to the front of the Ross Ice Shelf abutting Ross Island. One 140 km profile parallels and lies within about 10 km of the fresh shelf break while an adjacent 160 km profile bisects the iceberg. These two profiles are connected by two shorter profiles (approximately 35 and 45 km) running perpendicular from the fresh shelf break all the way to the former shelf edge. Along its centerline (parallel to the former shelf edge) B15a ranges from about 200 to 270 m in thickness. In the shorter perpendicular lines the ice thickness thins rapidly to less than 100 m as the former shelf edge is approached. Our objective of simultaneously imaging high-resolution surface and bottom scatterers as well as the extremely subtle englacial layering was also achieved.

C52B-02 1615h

Geothermal Flux, Basal Melt Rates, and Subglacial Lakes in Central East Antarctica

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The lakes beneath the East Antarctic ice sheet represent a unique environment on Earth, entirely untouched by human interference. Life forms which survive in this cold, lightless, high pressure environment may resemble the life forms which survived through snowball earth and evolved into the life forms we know today (Kirchvink, 2000). Recent airborne radar surveys over Dome C and the South Pole regions allow us to assess where these lakes are most likely to exist and infer melting and freezing rates at base of the ice sheet. Lakes appear as strong, flat basal reflectors in airborne radar sounding data. In order to determine the absolute strength of the reflector it is important to accurately estimate signal loss due to absorption by the ice. As this quantity is temperature sensitive, especially in regions where liquid water is likely to exist, we have developed a one dimensional heat transfer model, incorporating surface temperature, accumulation, ice sheet thickness, and geothermal flux. Of the four quantities used for our temperature model, geothermal flux has usually proven to be the most difficult to assess, due to logistical difficulties. A technique

developed by Fahnestock et al 2001 is showing promise for inferring geothermal flux, with airborne radar data. This technique assumes that internal reflectors, which result from varying electrical properties within the ice column, can be approximated as constant time horizons. Using ice core data from our study area, we can place dates upon these internal layers and develop an age versus depth relationship for the surveyed region, with margin of error of $\pm 50 \text{ m}$ for each selected layer. Knowing this relationship allows us to infer the vertical strain response of the ice to the stress of vertical loading by snow accumulation. When ice is frozen to the bed the deeper ice will accommodate the increased stress of by deforming and thinning (Patterson 1994). This thinning of deeper layers occurs throughout most of our study area. However, analysis of dated internal layers over several bright, flat, lake-like reflectors reveals a very different age versus depth relationship in which deeper layers actually thicken with depth. This thickening of deep layers results from ice flowing in from the sides to accommodate significant liquid water production at the base of the ice sheet. This melt is occurring today and can be quantified. With our knowledge of melt rates we can begin to estimate inputs and assess hydrologic parameters for the subglacial lake systems of East Antarctica.

C52B-03 1630h

Secular Decrease in Gravity at a Site on the South-central Greenland Ice Sheet

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Changes in ice sheet elevation are direct measurements of variations in ice sheet volume. These are also frequently taken to be indicators of changes in ice sheet mass and so are of interest because of the implications of changing ice sheet mass on global sea level. Several generations of spaceborne radar altimeters have collected ice sheet elevation data and two new instruments will be coming on line. The time series of elevation measurements that is currently available and that will become available over the next 10 years is the object of much scientific attention for the reasons mentioned above.

There is no doubt that spaceborne and airborne systems are accurately measuring elevation change, but are they also measuring changes in ice sheet mass? This question is difficult to answer because although much of the ice sheet consists of nearly incompressible ice, the upper 10's of meters of the ice sheet consist of relatively low-density firn. The density can vary for a number of reasons including changes in accumulation rate and changes in temperature. For example, it may be that some of the current elevation change observed by spaceborne and airborne altimeters in Southern Greenland is due to increased surface melting and subsequent near surface refreezing resulting in the formation of super-imposed ice. This is a common phenomenon that could result in ice sheet lowering without a loss of mass and obviously, no impact on sea level.

Gravity provides a more direct measurement of ice sheet mass changes and satellite gravimetric missions, such as GRACE, are aimed at detecting ice sheet mass changes on continental scales. Surface observations can complement spaceborne measurements by providing information at smaller spatial scales. This is now possible with the advent of GPS and the ability to precisely navigate back to the same geodetic point on the ice sheet, which itself is moving. In this fashion it is possible to develop a record of secular changes in the surface gravity field. Known surface-elevation-changes can be removed using a standard free air correction. The residual represents changes in the local mass.

We measured surface gravity at three locations about a glaciological measurement site located on the South-central Greenland Ice Sheet. Gravity observations were made in 1981, 1993 and 1995 at three locations separated by about 20 km and that were part of a hexagonal network of geodetic and glaciological measurements. Gravity data were collected in conjunction with Doppler satellite measurements of position in 1981 and global positioning system measurements in 1993 and 1995. The use of satellite navigation techniques permitted reoccupation of the same sites in each year to within a few 10's of meters or better. After detrending the gravity data, making adjustments for tides and removing the residual effects of local spatial gradients in gravity, an average secular decrease in gravity of about 0.02 milligal/year is observed. The trend is consistent with a reported increase in surface elevation measured by repeated airborne laser altimeter, and surface Doppler satellite and GPS elevation measurements. We go on to discuss differences between the residual gravity anomalies after free air correction in terms of local mass changes. We conclude with a discussion of the implications of our study on the interpretation of spaceborne altimetry measurements.