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 acreted 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 asses, 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 +- 50 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 superimposed 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.

C52B-04 1645h

Surface and Bottom Morphology of Petermann Gletscher's Floating Tongue in Northwestern Greenland

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Petermann Gletscher is the largest and most influential outlet glacier in central northern Greenland. Located at 81 N, 60 W, it drains an area of 71,580 km2, with a discharge of 12 cubic km of ice per year into the Arctic Ocean. Remote sensing results suggest that its ice discharge exceeds that required to maintain the ice sheet interior in a state of mass equilibrium by 63 percent, and its grounding line is retreating at a rate which indicates ice thinning at nearly one meter per year. Its floating ice tongue is only a few meters above sea level at the ice front, hence highly vulnerable to ice thinning.

A detailed field campaign was carried out in May and June 2002 on the floating ice tongue of the Petermann Gletscher, which will allow for the first time field observations to be integrated with remote sensing data. The experiments were done close to the grounding line, the most crucial part of the glacier. Bottom melt rates were estimated using a novel phase-sensitive radar sounding system developed by the British Antarctic Survey. The surface energy balance was measured with automated micrometeorological stations, and surface melt rates were monitored continuously with sonic height instruments throughout the summer. Tidal constituents were measured close to the grounding line to characterize tides using a GPS receiver. We will report first results from this field expedition, including interesting surface morphological features, ground penetrating radar profiles showing surface and bottom topography of a small region of the floating tongue, and possibly bottom melt rates derived by the phase sensitive radar.

C61A MCC: 130 Saturday 0830h

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

Presiding: **S Marshall,** University of Calgary**; T Murray,** University of Leeds

C61A-01 0835h

Englacial Water Flow - The Absence of Röthlisberger Conduits

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We investigated the englacial hydrology of Storglaciären, a polythermal glacier in northern Sweden, to provide empirical data to test models of englacial water movement proposed by Röthlisberger and others. Our investigations included both ice-penetrating radar surveys and boreholes drilled to provide direct access. In two cases englacial channels were first identified in radar surveys, which determined the channel position to within approximately one-meter. Radar surveys also identified isolated water-filled cavities, confirmed by drilling, within the surface cold layer. Radar results are described in more detail in a companion paper by Jacobel et al., (this session).

Boreholes were drilled using a hot-water system and a permanent drop in water level from the surface indicated interception of an englacial channel. After connection a submersible camera was lowered to image the geometry and orientation of the channel and to measure the water flow speed. Tracers were also injected to estimate connectivity between holes as well as flow speeds. Over two field seasons, we drilled 43 holes for a total distance of 3.7 km and down to depths of 200 m. Englacial channels were intercepted in 31 (72%) holes at depths between 10 and 158 m. In no instance did we encounter a Röthlisberger-type conduit. Instead we intersected steeply sloping crevasse-like features with nominal widths of 1 - 10 cm. Tracers and pressure variations revealed that the boreholes were englacially connected across 10s of meters despite connection depths that differed by 10 m or more. When flow could be detected, it was laminar with flow speeds between 0.1 - 1 cm s^{-1}.

From these results, we believe that crevasse-like features are the main conveyors of englacial water and form a fracture-like network consisting of numerous pathways, similar to a fracture network in rock rather than the traditional view of a few melt-enlarged conduits in ice. Classic Röthlisberger-type conduits are probably a special case of the flow system occurring only where flow paths converge to create discharges sufficient to initiate turbulent flow and melt-enlargement. Such locations would be limited to the glacier margins and near the terminal margin. These results counter current notions of englacial water flow and have profound consequences for past interpretation of data gained from boreholes and for understanding of water flow through glaciers.

C61A-02 0850h INVITED

Ice-sheet Hydrology and the Deglaciation of North America

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Geophysical, geological, and paleoceanographic records provide clues that basal hydrology was an important influence on the history and dynamics of the Laurentide ice sheet, particularly during deglaciation. Water at the bed of a glacier facilitates basal motion (through sliding and bed deformation), which is believed to have exerted a controlling influence on the geometry of the ice sheet and the activity of its surge lobes. This has motivated various parameterizations of hydrology in large-scale dynamical models of the Laurentide ice sheet. We propose a physically-based distributed model of ice-sheet hydrology that includes groundwater transport coupled to a more efficient drainage system at the ice–bed interface. Groundwater transport rates are largely determined by the local geology, while basal flow rates are a function of the temporally-variable drainage morphology. Driven by ice-sheet geometry and meltwater production, the hydrology model determines spatial distributions of basal water volume, pressure, and flux. These variables illuminate areas disposed to subglacial water storage and basal flow enhancement. Explicit treatment of the basal water system enables us to explore and quantify the feedbacks of hydrology on Laurentide ice-sheet dynamics during the last deglaciation.

C61A-03 0905h

Real-time Hydrologic Observations of Hidden Creek Lake Jökulhlaups, Kennicott Glacier, Alaska

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Few glacier outburst floods (jökulhlaups) have been monitored in detail as they occur. Hidden Creek Lake (HCL), an ice-marginal lake impounded by Kennicott Glacier, Wrangell Mountains, Alaska, fills annually to a volume of about 20 to 30 million m^3 and then drains subglacially within about 2 to 3 days. In 1999, we measured lake-surface elevation, ice-dam deformation, and discharge in the Kennicott River (which drains the glacier) during the HCL outburst floods. In 2000 we collected comparable data beginning 3 weeks before lake drainage, and also measured flow in Hidden Creek, the main source of HCL water. Sources and sinks were in balance; any leakage from HCL prior to the 2000 jökulhlaup was too small to resolve. An important complication revealed by the deformation data was water storage in a "wedge" beneath the ice dam. During the 3 weeks before drainage in 2000, at least 1/3 of the total input to HCL went into the subglacial "wedge". The HCL outflow hydrograph was determined from lake-level records, basin hypsometry, and measured downdrop of the ice dam. In both 1999 and 2000, about 20% of the total water volume was stored in the subglacial "wedge". Both hydrographs were considerably more symmetrical about the peak than the canonical jökulhlaup hydrograph commonly mentioned in the literature. The relatively long tail on the outflow hydrograph may have been due to the fact that the entire lake had to evacuate through the subglacial "wedge", which became progressively more constricted with time. The flood hydrograph measured near the glacier terminus (16 km from the lake) is also fairly symmetrical. The flood peak in both years occurred about 12 h after the peak in the outflow hydrograph, implying a mean transit time of about 0.4 m/s. Integrated flood volume and lake volume agree fairly well in both years. Water-quality measurements are difficult to interpret: suspended sediment concentration in flood water peaked about 12 h before discharge, and the chemistry of flood waters is not readily explained by any sort of simple mixing models. As the HCL outburst flood progresses, Donoho Falls Lake–a normally dry ice-marginal basin that fills and drains during the HCL jökulhlaup–filled with water whose chemistry was closer to that of the background flow in Kennicott River than to HCL water, suggesting that the outburst flood created high subglacial water pressure that impeded normal drainage and even caused flow direction locally to reverse. Water levels recorded in boreholes also indicate the HCL jökulhlaup caused widespread disturbance in the glacier's pre-existing drainage system.

C

C61A-04 0920h

Hydraulics of Supraglacial Outburst Floods

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A substantial literature exists describing observations and theory of subglacial outburst floods. Episodic floods from the Grímsvötn reservoir within the Vatnajökull ice cap of Iceland are especially well documented and have inspired some of the most influential theoretical developments. Much of this work is focused on physical processes and hazard prediction and applications to paleohydrology are uncommon. In contrast to subglacial outburst floods, the study of supraglacial outbursts is in an early stage of development. Such events are extremely rare and therefore challenging to study, yet supraglacial release is a conceivable mechanism for some of the great floods of the Pleistocene era, for which no modern analogues exist. For most of these reservoirs there are no data to distinguish whether the flood mechanism was supraglacial or subglacial so that, in addition to relevant but poorly constrained variables such as water temperature, the release mechanism itself is uncertain. A recent contribution by *Raymond and Noll* [2000] marks the first attempt to identify the controlling processes and encapsulate them in a physical model. However the work relies on a simplifying "bottleneck" assumption that is likely to be inappropriate when applied to the very long flood channels that would be required for supraglacial outburst floods from huge proglacial lakes of the Pleistocene and early Holocene epochs. Thus no existing models are appropriate for paleohydraulic comparisons of subglacial and supraglacial outbursts. Here I present a new model of supraglacial outburst flooding that is rooted in the Spring-Hutter formalism and does not suffer from the bottleneck assumption. Interesting complications arise such as the possibility of a spatially migrating spillway and overflow from the outlet channel onto the ice sheet surface.